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Economic and Environmental Analysis of Technologies to Treat Mercury and Dispose in a Waste Containment Facility

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ECONOMIC AND ENVIRONMENTAL ANALYSIS OF TECHNOLOGIES TO TREAT MERCURY AND DISPOSE IN A WASTE CONTAINMENT FACILITY

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NOTICE

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FOREWORD

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Sally Gutierrez, Director
National Risk Management Research Laboratory

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ACRONYMS

AHP	Analytic Hierarchy Process
ASTM	American Society for Testing and Materials
BNL	Brookhaven National Laboratory
CFR	Code of Federal Regulations
COTR	Contracting Officer's Technical Representative
CQA	Construction Quality Assurance
CTA	Centralized Treatment Alternative
DLA	Defense Logistics Agency
DNSC	Defense National Stockpile Center
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
HDPE	High Density Polyethylene
LCCE	Life-Cycle Cost Estimate
LCRS	Leachate Collection and Removal System
LDR	Land Disposal Restrictions
LDS	Leak Detection System
ME	Macroencapsulation
MT	Metric Tons
MTA	Mobile Treatment Alternative
NME	No Macroencapsulation
MMEIS	Mercury Management Environmental Impact Statement
NEI	Nuclear Energy Institute
NPV `	Net Present Value
O&M	Operations and Maintenance
OMB	Office of Management and Budget
ORD	Office of Research and Development
OSW	Office of Solid Waste
PBT	Persistent, Bio-accumulative, and Toxic
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SEK	Swedish Kroner
SPSS	Sulfur Polymer Solidification/Stabilization Process
TCLP	Toxicity Characteristic Leaching Procedure
TLV	Threshold Limit Value
UTS	Universal Treatment Standard
WF	Weighting Factor
WIPP	Waste Isolation Pilot Plant

ECONOMIC AND ENVIRONMENTAL ANALYSIS OF TECHNOLOGIES TO TREAT MERCURY AND DISPOSE IN A WASTE CONTAINMENT FACILITY

EXECUTIVE SUMMARY

This report is intended to describe an economic and environmental analysis of a number of technologies for the treatment and disposal of elemental mercury.[1] The analysis considers three treatment technologies that convert elemental mercury into a stable form of mercury. The technologies are identified as Option A, Option B, and Option C in this report. Several vendors use processing techniques and/or prepare economic information which has been claimed as proprietary; however, only non-proprietary information is presented in this report.

Each of the three treatment technologies is subject to a number of variations that include either a centralized treatment facility or one or more mobile treatment facilities, followed by either macroencapsulation or no macroencapsulation[2], with ultimate disposal in a monofill. Thus, there are twelve treatment and disposal alternatives all together:

1. Option A + no macroencapsulation + centralized treatment
2. Option A + no macroencapsulation + mobile treatment
3. Option A + macroencapsulation + centralized treatment
4. Option A + macroencapsulation + mobile treatment
5. Option B + no macroencapsulation + centralized treatment
6. Option B + no macroencapsulation + mobile treatment
7. Option B + macroencapsulation + centralized treatment
8. Option B + macroencapsulation + mobile treatment
9. Option C + no macroencapsulation + centralized treatment
10. Option C + no macroencapsulation + mobile treatment
11. Option C + macroencapsulation + centralized treatment
12. Option C + macroencapsulation + mobile treatment

Three different masses of mercury are being considered for each of the 12 alternatives:

a. 5,000 metric tons,
b. 12,000 metric tons, and
c. 25,000 metric tons.

Thus, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all. It is assumed that 1,000 MT per year is treated and disposed of independent of the total mass. For the storage alternatives, it is assumed 5,000 MT is already in storage (approximately consistent with the existing amount in government stockpiles) and that the additional elemental mercury becomes available over 12 and 25 years respectively for the 12,000 MT and 25,000 MT alternatives (e.g., due to chlor-alkali plant closure).

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[1] Note – the analysis is restricted to the treatment and disposal or long-term storage of elemental mercury. This report does not consider the treatment and disposal of mercury-containing wastes nor radioactive mercury.

[2] No other waste will be commingled with the treated mercury in these monofills. Macroencapsulation in this report is a separate step after stabilization during which the treated mercury is sealed in polyethylene to limit mercury transport to the environment. If the stabilization process ends with the solidified product in some form of container, this container will be encapsulated in polyethylene in the macroencapsulation alternative. "No macroencapsulation" means that the stabilized mercury will be placed in the monofill exactly as it is generated by the stabilization process.

The results are presented in Section S.5 of this summary with conclusions and recommendations in Section S.6. Sections S.1 through S.4 discuss the background, approach and assumptions.

S.1 Background

The use of mercury in products and processes is decreasing. It is likely that in the future, the supply of mercury will far exceed the demand for mercury. In addition, the Department of Defense (DOD) and the Department of Energy (DOE) have stockpiled approximately 6,000 Metric Tons (MT) of mercury that is no longer needed. Therefore, strategies must be devised for managing the excess mercury. Currently, the most prevalent method is to store the elemental, liquid form in flasks and stockpile them in warehouses. The risks associated with this method of storing elemental mercury have been extensively discussed in the *Final Mercury Management Environmental Impact Statement* (DLA 2004).

Independently of DLA, EPA's Offices of Research and Development (ORD) and Solid Waste (OSW) have been working with DOE to evaluate technologies for permanently stabilizing and disposing of wastes containing mercury (e.g., DOE 1999a-1999e; USEPA 2001, 2002a,b). Other comprehensive studies carried out in the recent past include one by SENES Consultants (SENES 2001) who produced a draft report for Environment Canada evaluating 67 technologies for the retirement and long-term storage of mercury. In addition, OSW is considering revisions to the Land Disposal Restrictions (LDRs) for mercury. Land disposal of hazardous wastes containing greater than 260 mg/kg mercury is currently prohibited. OSW has pursued options which would allow land disposal of waste containing greater than 260 mg/kg mercury; however, no specific revisions are forthcoming (See Section 1.1 of this report for further information).

Using the above-referenced work as a starting point, EPA prepared report EPA/600/R-03/048, *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). USEPA (2002c) Appendix B provides a concise review of the SENES 2001 mercury treatment technologies and why certain treatment technologies were not selected by the USEPA for further analysis. The purpose of the present work is the logical next step, which is to focus on just a few of the alternatives considered in EPA/600/R-03/048. This allows a more detailed breakdown and analysis of the stabilization/amalgamation alternatives than was possible in EPA/600/R-03/048, and also allows more effort to be applied to developing cost information.

S.2 Choice of Technologies

The first task was to narrow the choice of treatment technologies to just three.

The first step was to review the available literature and to hold consultations with EPA personnel in ORD and OSW. This resulted in a short-list of 6 treatment technologies identified as Options A through F. The list was then winnowed down to 3 treatment technologies by using the Kepner-Tregoe decision-making method as a tool[3]. Section 1.3.1 contains a brief summary of this method. It is further described in Section 2 and its use resulted in a final list of three treatment technologies, Options A, B, and C. See DOE (2001a).

S.3 Environmental Analysis

The method chosen for the environmental comparison of the twelve treatment and disposal alternatives is the Analytic Hierarchy Procedure (AHP) as embodied in the Expert Choice software. This is the same tool that was used for the analysis in EPA/600/R-03/048. Different selection criteria were used in the present AHP analysis than in the USEPA 2002c study to better define the

[3] The Kepner-Tregoe method assigns a weight to each of a number of selected criteria. Each alternative is then scored against each criterion (e.g., on a scale from 1-10). The scores and corresponding weights are multiplied and then summed for each criterion, leading to a numerical ranking.

strengths/weaknesses and data gaps of each treatment technology. The AHP process is described in Section 1.3.2. Information and details of Expert Choice software and its usage are described in Appendices A and B.

The AHP was carried out as a brainstorming exercise by a team from SAIC and EPA. The team first developed the goal of the analysis: minimize environmental impacts during the life-cycle of the treatment and disposal of elemental mercury. Based on this goal, the team then developed and ranked criteria against which each alternative was compared. Criteria with largest weight and smallest rank as the most important issues. These criteria and subcriteria with relative weightings and rankings are provided in parentheses were:

C1. During routine operation of the stabilization facility (weighting: 0.065, ranking: 4)
- C1-1. -solid waste streams (other than final product) (0.750)
- C1-2. -atmospheric discharges (0.250)

C2. During abnormal or accidental operation of the stabilization facility (weighting: 0.188, ranking: 3)
- C2-1. -elemental mercury spills (0.833)
- C2-2. -spills other than elemental mercury (0.167)

C3. During transportation (weighting: 0.216, ranking: 2)
- C3-1. -of mercury to stabilization facility (0.747)
- C3-2. -of stabilized waste to monofill (0.119)
- C3-3. -of reagents to stabilization facility (0.134)

C4. During decommissioning of the stabilization unit (weighting: 0.038, ranking: 5)

C5. During storage in the monofill (weighting: 0.493, ranking: 1)
- C5-1. - expected difficulty of maintaining environmental conditions (up to 40 years) (0.200)
- C5-2. -expected long-term susceptibility to degradation (0.800)

The weights against each criterion or subcriterion are an indication of the relative importance and were assigned by the team using a brainstorming process known as “pairwise comparison.” The relative importance of criteria, from most to least is shown in Figure S-1. Each of the 12 treatment and disposal alternatives were then assigned an “intensity” or score relative to each of the criteria or subcriteria. Section 3.3 and USEPA 2002c provide details on “pairwise comparisons” and “intensities”. Summing these scores leads to a relative ranking of the alternatives, see Section S.5.

The above weightings show that, of the first-level criteria, the SAIC/EPA team assigned the greatest weight (almost 50%) to storage in the monofill. Of the subcriteria below storage in the monofill (C5-1 and C5-2), the greatest weight (80%) was assigned to the long-term susceptibility of the waste form to degradation (e.g., changes in the disposal environment as discussed in Section 3.3.5 and Appendix B). Therefore, scores for individual alternatives were strongly influenced by the team’s expectations about long-term behavior in the monofill.

The team also assigned considerable importance to transportation accidents, especially those that could involve the spillage of elemental mercury.

S.4 Economic Analysis

As described above, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all.

Each of the thirty-six cost estimates for treatment and disposal includes the following elements[4]:

[4] Note: the cost results do not contain estimates of the costs that might be incurred should there be an accident or malfunction (e.g., a spillage of elemental mercury during transportation or excessive leachate escaping from the monofill).

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative),
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternatives,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment,
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

The SAIC team developed process flow diagrams for each of the three technologies and the associated macroencapsulation process and a preliminary design for the monofill such that 1,000 MT of elemental mercury will be treated and disposed of each year.

The sources of information for the cost estimates included:

- Published work by the vendors of Options A, B, and C together with information gathered in telecons. This enabled the team to develop the 1,000-MT/year process flow diagrams and to obtain some information on costs.
- Code of Federal Regulation requirements for the construction and operation of a monofill.
- Standard industry sources of cost information such as Perry and Green's *Industrial Engineering Handbook* and Richardson Engineering Services' *Process Plant Construction Estimating Standards*.
- Telecons with equipment manufacturers.
- Websites of equipment manufacturers.
- The Mercury Management Environmental Impact Statement (MMEIS), published by the Defense Logistics Agency (DLA 2004). This contains detailed information on storage and transportation costs.

The SAIC team assigned uncertainty ranges to items that are input to the total cost. The final cost estimates and uncertainties were estimated by performing an uncertainty analysis using a triangular probability distributions in Crystal Ball® software (Decisioneering 2004)[5]. See Section 4.5 for a discussion of how input ranges of uncertainty were assigned.

S.5 Results

This section considers first the results of the environmental analysis and then the results of the economic analysis. The results from the environmental evaluation were considered independently from the economic evaluation (i.e., results from the environmental evaluation had no effect on the economic evaluation and vice versa). In principal, the economic viability of the various alternatives could have been considered as one of the top-level criteria in the AHP analysis, but this was not part of the scope of

[5] Crystal Ball® is user-friendly software that facilitiates the performance of Monte Carlo-type analyses by linking to data in Excel spreadsheets.

the present analysis. An example of an AHP study in which both economic and environmental factors were considered can be found in USEPA (2002c).

S.5.1 Environmental Analysis – Results

Table S-1 shows the results for the twelve treatment and disposal alternatives (independent of mass). The AHP process scales all values to 100 percent. Thus the more alternatives analyzed the smaller the values for each alternative. The values in Table S-1 should be considered as being relative to each other, not as absolutes. The values in Table S-1 are normalized to 1000 points to make them whole numbers. The following are some observations derived from Table S-1:

- In general, mobile treatment alternatives score better than centralized treatment alternatives. The principal reason for this is that the authors made a simplifying assumption: for the centralized treatment alternatives, elemental mercury is transported to the central treatment unit, whereas the mobile treatment facility travels to the elemental mercury, in which case only the waste product is transported. In Section S.3, the transportation criterion (C.3) is assigned a weight of 0.216, with only the monofill being of greater concern. See Figure S-1 for the relative importance of each criteria and subcriteria. Of the transportation subcriteria, accidental mercury releases are assigned by far the greatest weight (0.747) so that alternatives in which mercury can be released during transportation have a relatively large unfavorable impact on the total score. Data and assumptions used by DLA (2004) were used to assess risks from mercury transport; these data are in Appendix A.
- There is a slight preference towards macroencapsulation alternatives over alternatives that do not include this additional treatment. This is principally because the polyethylene-macroencapsulated waste is expected to behave relatively well in the monofill and decrease the potential long-term leachability of mercury.
- All of the alternatives that include Option B technology score higher than options which include Option C technology. This is because the Option B waste form has a lower leaching rate in the monofill than does the Option C waste form (see Figure B-1 in Appendix B) and the Option B leaching rate is much less sensitive to changes in pH than is Options C. In addition, currently available data on the Option C technology suggest a relative high rate of volatilization of mercury, which in itself could present a release pathway and could also lead to decreased effectiveness (through deformation) of the encapsulation material over time (discussed in Appendix B).
- Cases which include Option A technology are more scattered; one Option A case scores highest while a different Option A case scores lowest. The Option A cases without macroencapsulation tend to score low because available data (see Figure B-1 in Appendix B) suggest that leaching rates from the Option A waste form are quite sensitive to small changes in pH. This conclusion should be caveated by noting that there are large uncertainties in the leaching results presented on Figure B-1.

The above observations were confirmed by performing analyses that addressed uncertainties by changing the intensities assigned to the various options. For example, changing the intensities of the four Option C cases to reflect relatively good environmental performance in the monofill considerably increased their scores and improved their ranking. In addition, the authors conducted a selection of sensitivity analyses on the relative importance of the criteria, as follows:

- Changing the weight of the final disposal criterion from 49.3% to 75% (i.e., more important)
- Changing the weight of the final disposal criterion from 49.3% to 25% (i.e., less important)
- Changing the weight of the transportation criterion from 21.6% to 40% (i.e., more important)
- Changing the weight of the transportation criterion from 21.6% to 10% (i.e., less important)

- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 40% (i.e., more important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 10% (i.e., less important)
- Changing the weight of the routine operations criterion from 6.5% to 13% (i.e., more important)
- Changing the weight of the routine operations criterion from 6.5% to 3.2% (i.e., less important)
- Changing the weight of the decommissioning criterion from 3.8% to 7.6% (i.e., more important)
- Changing the weight of the decommissioning criterion from 3.8% to 1.8% (i.e., less important)

In each case the weights of the remaining criteria were changed (while keeping their relative magnitudes the same) to ensure that the sum of all the weights is 100%. The results of the analyses of the three most sensitive criteria, which are the first six bullets listed above, are shown in Table S-2. The remaining sensitivities are presented in Appendix A and are not presented here because they produce very small differences in the scores.

In all cases, the same two alternatives remain the most highly ranked for both the baseline analysis and the ten sensitivity analyses (i.e., Option A and Option B with mobile treatment and macroencapsulation). At the other extreme, the same single alternative remained the most unfavorably ranked in all cases (i.e., Option A with centralized treatment and no macroencapsulation). In between, there are minor changes in ranking. This helps show the stability in the results.

In addition to sensitivity analyses, the Team also performed uncertainty analyses. Uncertainty identifies the extent to which variation in the information and data influences the conclusions. Some of the areas of uncertainty include the following (see Appendix B):

- <u>Monofill Disposal Stability for Option C- long term</u>: Conflicting data are available regarding the degree of mercury vapor generation from the Option C process, which is an area of uncertainty affecting stability. Table S-3 shows that, if the long-term behavior of Option C-generated waste in the monofill is better than assumed in the base case, its ranking improves considerably. This issue is discussed in more detail in Section 3.8.
- <u>Monofill Disposal Stability for Option A</u>: As discussed above, a single alternative scored lowest in all sensitivity analyses (i.e., centralized treatment of Option A with no macroencapsulation). As an uncertainty analysis, intensity values of this alternative were changed to demonstrate how its score may rise, as follows:

    - Option A + no macroencapsulation + centralized treatment. Original score 48 (12^{th} highest)
    - Analysis 1: Changing intensity of <40 year disposal condition from ‘moderate’ to ‘low’: slight increase in score to 55 (12^{th} highest)
    - Analysis 2: Changing intensity of >40 year disposal condition from ‘moderate’ to ‘low’: significant increase in score to 84 (6^{th} highest)
    - Analysis 3: Changing intensity of both the <40 year and >40 year disposal condition from ‘moderate’ to ‘low’: significant increase in score to 92 (4^{th} highest)

This illustrates that consideration of sensitivities and uncertainties must be an important factor in decision-making. The recommendations below include one that addresses the desirability of obtaining better leaching data before making final choices between alternatives.

- Other Monofill Disposal Stability: An obvious area of uncertainty for all alternatives is the degree to which the disposal conditions will remain stable for both a short and a long period of time (less than 40 years and greater than 40 years, respectively). This range was demonstrated for one of the alternatives. In addition, the scale-up performance of the treatment technologies themselves is uncertain with regard to their ability to treat relatively large quantities of mercury for an extended period of time. In all cases, good mixing and operational consistency are expected to be critical in achieving long-term stability.
- Accidental Releases of Mercury During Operations: Risks of accidental releases of mercury during the mercury treatment step may be higher or lower than evaluated. This range was demonstrated for two of the alternatives.

The uncertainty analyses and results are described in Table S-3. Each row of the table represents an instance where data are changed for just one of the alternatives. As shown, a total of 11 different uncertainty analyses were conducted.

The 11 sets of uncertainty analysis results in Table S-3 show how the overall ranking of each alternative is affected as the intensities of individual criteria are changed. It would be expected that the largest changes in ranking would result from changing the subcriteria with the largest relative weights, i.e., the weight of the subcriteria times the weight of the criteria. As seen from Figure S-1 long-term disposal subcriteria has the largest relative weight.

As would be expected if the model worked properly, the uncertainty analyses showed that results change most significantly in the case of changing the intensity of the long term (>40 year) disposal criterion between 'Moderate' and 'Low.' This is shown for Reference Nos. 1 through 7. For example, as discussed above, the lowest-scored Option A alternative in Table 3-4 (Reference No. 3) significantly improves its score, from 48 (12^{th} best) to 84 (6^{th} best). Changes in the intensity of the shorter term (<40 year) value also improve the score, but not as much (Reference Nos. 2 and 4).

Uncertainty with regard to accidental releases (mercury spills) during operations have a relatively small effect on results. For example, an Option B alternative (Reference Nos. 8 and 9) still ranks high regardless of whether the intensity is given a value of low, moderate, or high.

The uncertainty analysis can be used to identify important parameters in which further research may be required. That is, particular attention could be placed on uncertain data, which significantly affect the results. As shown above, this suggests that uncertainty with regard to long-term storage and disposal represents one such parameter.

S.5.2 Economic Analysis – Results

The results of the economic analysis are shown in Tables S-4 and S-5. The results are presented as Net Present Values (NPV), for which the team used the OMB 30-year real discount rate of 3.5% per year. Note that the "best" estimates are the means that result from the Monte Carlo analysis and are not necessarily exactly the same as would result from a sum of point estimates without uncertainty distributions. Tables S-4 and S-5 prompt a number of observations and conclusions.

- The most striking result is that the Option C cases cost far more than do the others. Analysis of the calculations reveals that there is one parameter that drives almost the whole of this difference – the cost of reagents. The cost was provided by the vendor for the amalgamation and stabilization of elemental mercury. No attempt was made to adjust it for potential economies of scale. The actual cost of reagents for the Option C process is proprietary and cannot be quoted here but calculations show that the NPV for Option C reagent costs alone for the 5,000 MT case is approximately $123M. For Option A the comparable costs are approximately $8M and for Option B approximately $3.4M. Therefore, for the alternatives that treat 5,000MT, the reagent costs alone account for more than $100M difference between the costs of Option C process and those of the Option A or Option B processes, with correspondingly larger differences for the 12,000 MT and 25,000 MT alternatives.

- As noted, the composition of the Option C reagents is proprietary. In any future decision making process, the cost per kg of treated Hg will need to be examined in more detail.
- The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies – the mass multipliers for waste form production are 1.63 (Option B), 3.26 (Option A), and 5.66 (Option C)[6] . This affects other items such as transportation costs.
- The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands assigned to mobile treatment alternatives –20% to +200% for capital costs and –50% to + 100% for O&M costs. These wide ranges were assigned because the mobile treatment option is not well defined (e.g., the number of treatment units is not known). There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site.
- The cost of storage is relatively modest. Note that these storage costs were derived from data in the MMEIS. For example, for continued storage of 5,000 MT for 35 years, the NPV is \$11.6M. Continuing to store elemental mercury for years or even decades is a reasonable course of action.

S.6 Conclusions and Recommendations

- One key reason why the Option C process alternatives fall in the bottom half of Table S-1 is that the team assigned considerable importance to what is known about mercury vapor evolution from the Option C waste form. However, the data in this area are not of high quality and further research is needed to confirm that this relatively unfavorable weighting of the Option C process is justified.
- The data on leaching performance as a function of pH strongly favor Option B (see Figure B-1 in Appendix B). There is considerable scatter in the leaching data for the other two processes. Further research in this area could help to provide greater confidence in the stability of waste forms in typical monofill environments.
- The effectiveness of macroencapsulation in the long term is uncertain. Further assessment of the long-term effectiveness of macroencapsulation would be valuable.
- As noted above, the predicted cost of the Option C cases is much greater than those of the other two processes. A large portion of this difference can be attributed to reagent costs. It would be useful to perform an investigation to see whether the Option C process can be run with a cheaper mix of reagents, or whether economies of scale might lead to reduced costs in this area. Since the mix of reagents in the Option C process is proprietary (but not in the other two cases) it was not possible to perform any further analyses in the course of this project.
- The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies. This affects other items such as transportation costs.
- The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands on mobile treatment alternatives –20% to +200% for capital costs and –50% to + 100%

[6] See Sections 4.1.2.1, 4.1.2.2, and 4.1.2.3 for discussion of these multipliers.

for O&M costs. There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site. The mobile treatment alternative needs to be much better defined if the uncertainty bands are to be reduced.

- The storage alternatives are reasonably economical and, as shown in the previous report EPA/600/R-03/048 do not pose large environmental risks. It would still be cost effective to continue to store elemental mercury for a number of years or decades in anticipation that there might be a breakthrough in treatment technologies.

Table S-1. Environmental Analysis - Summary of Baseline Results for 12 Evaluated Alternatives

Treatment Scenario			Overall Ranking	
Treatment Process	Macro-Encapsulation	Fixed or Mobile Facility	Score (as fraction of 1,000)	Rank (Best to Worst)
Option A	With	Mobile	117	1
Option B	With	Mobile	117	1
Option B	Without	Mobile	108	3
Option A	With	Fixed	98	4
Option B	With	Fixed	98	4
Option B	Without	Fixed	89	6
Option C	Without	Mobile	73	7
Option C	With	Mobile	73	7
Option A	Without	Mobile	66	9
Option C	Without	Fixed	57	10
Option C	With	Fixed	57	10
Option A	Without	Fixed	48	12
Number of alternatives evaluated			12	—
Total			1,000	—
Average score (total divided by 12, the number of alternatives)			83	—

Shading indicates the highest-ranking alternatives.
Distributive mode; overall inconsistency factor from Expert Choice software: 0.02 (good).
Average value is provided for reference and identifies the average score for the twelve evaluated technologies.

Table S-2. Environmental Sensitivity Analysis

Treatment Scenario			Ranking[a]													
			Baseline (from Table S-1)		Importance on Disposal				Importance on Transport				Importance on Accidents			
Treatment Process	Macro-Encapsulation	Fixed or Mobile Facility			Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low	
			Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Option A	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	Without	Mobile	108	3	111	5	105	3	113	3	105	5	101	3	110	3
Option A	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	Without	Fixed	89	6	102	6	78	9	79	9	96	6	88	6	90	6
Option C	Without	Mobile	73	7	60	7	85	5	84	7	66	7	76	7	72	7
Option C	With	Mobile	73	7	60	7	86	4	85	4	66	7	76	7	72	7
Option A	Without	Mobile	66	9	48	11	84	6	81	8	57	11	71	9	64	9
Option C	Without	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option C	With	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option A	Without	Fixed	48	12	39	12	56	12	47	12	48	12	57	12	44	12
Average			83	—	83	—	83	—	83	—	83	—	83	—	83	—
Total			1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—

Shading indicates the highest-ranking alternatives. In the sensitivity analysis for each criterion, the importance of the criterion is set at higher or lower than its baseline value, as identified in the text. The four other criteria comprise the remainder, proportional to their original contributions.
a. Scores normalized to total 1,000.

Table S-3. Uncertainty Analysis for Mercury Management Alternatives

Ref. No.	Alternative			Criteria	Change in Intensity for Uncertainty Analysis		Initial Result (Table S-1)		Uncertainty Analysis Result	
					Baseline	Change	Score	Rank	Score	Rank
0	All			Baseline for comparison: Same results as Table S-2			—	—	—	—
1	**Treatment Process**	**Macro-Encapsulation**	**Fixed or Mobile Facility**	Monofill Disposal, >40 years	Moderate	Low				
	Option C	Without	Mobile				73	7	99	3
	Option C	With	Mobile				73	8	99	3
	Option C	Without	Fixed				57	10	82	6
	Option C	With	Fixed				57	11	82	6
2	Option A	Without	Fixed	Monofill Disposal, <40 years	Moderate	Low	48	12	55	12
3				Monofill Disposal, >40 years	Moderate	Low			84	6
4				Monofill Disposal, both <40 years and >40 years	Moderate	Low			92	4
5	Option B	With	Mobile	Monofill Disposal, <40 years	Low	Moderate	117	2	108	2
6				Monofill Disposal, >40 years	Low	Moderate			76	6
7				Monofill Disposal, both <40 years and >40 years	Low	Moderate			68	9
8	Option B	Without	Mobile	Accidental Releases (Mercury Spills)	Moderate	Low	108	3	117	1
9						High			102	3
10	Option C	With	Fixed		Moderate	Low	57	11	66	9
11						High			51	11

Table S-4. Net Present Value Estimates

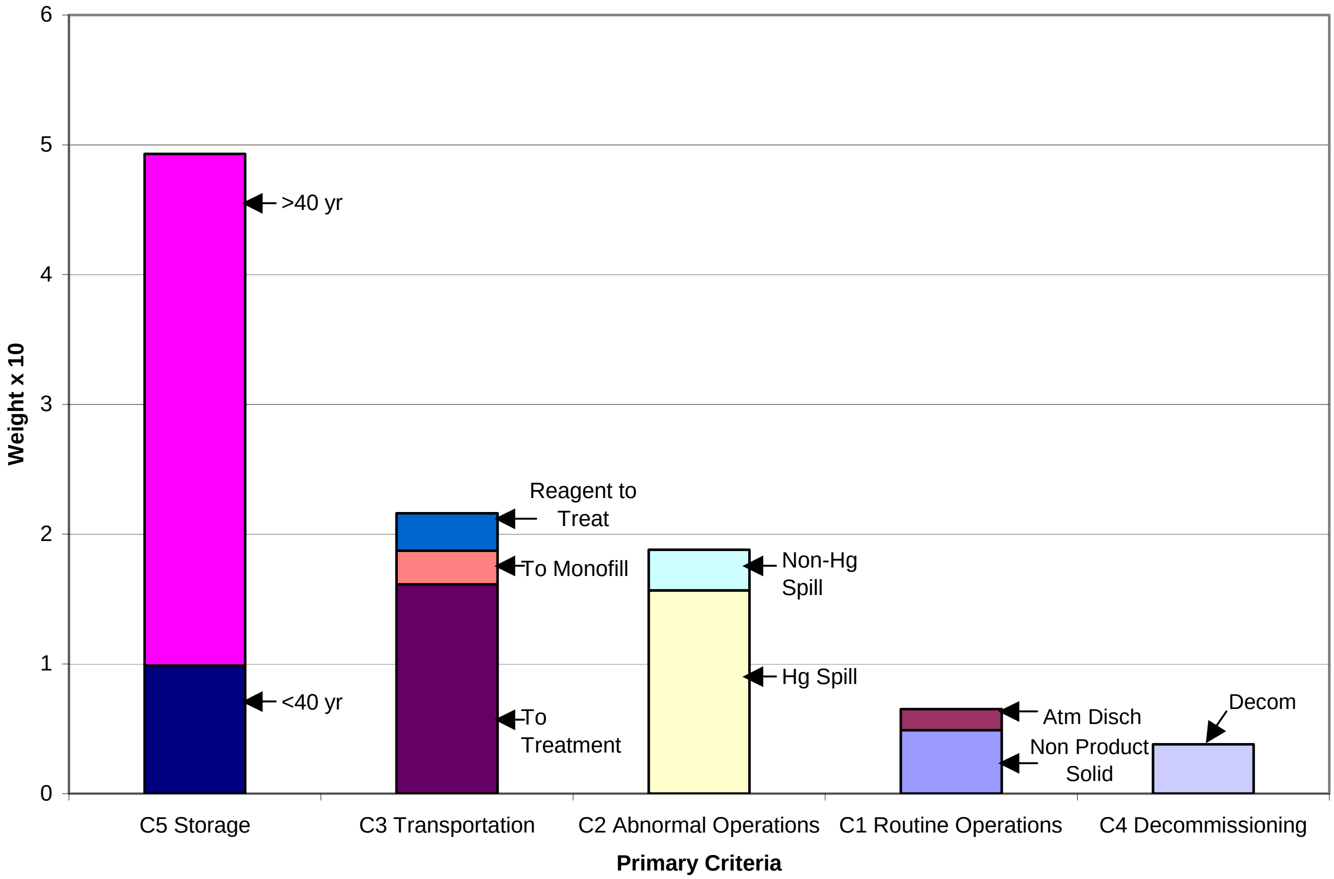
Treatment Scenario			Net Present Value Estimates in Millions of Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]
Option A	With	Fixed	77.1	82.7	89.0	149	161	174	245	265	287
Option A	With	Mobile	75.8	99.2	128	143	191	251	232	315	415
Option A	Without	Fixed	60.2	65.4	71.3	117	128	141	184	203	224
Option A	Without	Mobile	57.7	79.8	107	105	150	207	169	242	341
Option B	With	Fixed	32.3	34.3	36.4	62.2	66.2	70.6	102	109	116
Option B	With	Mobile	32.4	40.9	50.7	60.5	78.3	97.5	98.4	127	160
Option B	Without	Fixed	22.7	24.3	26.2	42.8	46.1	49.9	69.6	75.2	81.8
Option B	Without	Mobile	22.3	29.3	38.0	40.9	54.2	71.7	65.1	87.5	118
Option C	With	Fixed	162	178	197	342	378	418	579	639	707
Option C	With	Mobile	138	203	292	290	429	617	490	732	1,040
Option C	Without	Fixed	146	163	181	306	341	381	517	578	647
Option C	Without	Mobile	119	184	270	247	386	573	421	656	967
Long-Term Storage[d,e]			10.4	11.6	12.8	26.1	29.0	31.9	51.3	57.0	62.7

a. Fifth percentile of the distribution derived from the Crystal Ball® analysis.
b. Mean of the distribution derived from the Crystal Ball® analysis.
c. Ninety fifth percentile of the distribution derived from the Crystal Ball® analysis.
d. Not derived from Crystal Ball® analysis – best estimate based on MMEIS data (DLA 2004) with ±10% uncertainties.
e. Cost of shipping elemental mercury to the storage location not included. Upper bound transportation costs derived from MMEIS data are $0 (5,000 MT), $1.0M (12,000 MT), and $2.3M (25,000 MT). These are at most small percentages of the total cost of long-term storage.

Table S-5. Net Present Value Estimates Expressed as Cost per Metric Ton of Treated Mercury

Treatment Scenario			Net Present Value Estimates in Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**
Option A	With	Fixed	15,400	16,600	17,800	12,400	13,400	14,500	9,800	10,600	11,500
Option A	With	Mobile	15,200	19,800	25,600	11,900	15,900	20,900	9,300	12,600	16,600
Option A	Without	Fixed	12,000	13,100	14,300	9,800	10,700	11,800	7,400	8,100	9,000
Option A	Without	Mobile	11,600	16,000	21,400	8,800	12,500	17,300	6,800	9,700	13,600
Option B	With	Fixed	6,500	6,900	7,200	5,000	5,500	5,900	4,100	4,400	4,600
Option B	With	Mobile	6,500	8,200	10,100	5,100	6,500	8,100	3,900	5,100	6,400
Option B	Without	Fixed	4,500	4,900	5,200	3,600	3,800	4,200	2,800	3,000	3,300
Option B	Without	Mobile	4,500	5,900	7,600	3,400	4,500	6,000	2,600	3,500	4,700
Option C	With	Fixed	32,400	35,600	39,400	28,500	31,500	34,800	23,000	25,600	28,300
Option C	With	Mobile	27,600	40,600	58,400	24,200	35,800	51,400	19,600	29,300	41,600
Option C	Without	Fixed	29,200	32,600	36,200	25,500	28,400	31,800	20,700	23,100	25,900
Option C	Without	Mobile	23,800	36,800	54,000	20,600	32,200	47,800	16,800	26,200	38,900
Long-Term Storage			2,100	2,300	2,600	2,200	2,400	2,700	2,100	2,300	2,500

Figure S-1. AHC Criteria and Subcriteria Relative Weights



1.0 INTRODUCTION

This section provides background on the need for the long-term disposal of elemental mercury and discusses the outline of the remainder of this report.

1.1 Background

The use of mercury in products and processes is decreasing. It is likely that in the future, the supply of mercury will far exceed the demand for mercury. In addition, the Department of Defense (DOD) has stockpiled more than 4,800 tons of mercury that are no longer needed, and the Department of Energy (DOE) has also accumulated large volumes of elemental mercury. Therefore, strategies must be devised for managing the excess mercury. Currently, the most prevalent method is to store the elemental, liquid form in flasks and stockpile them in warehouses. The risks associated with this method of storing elemental mercury have been extensively discussed in the *Final Mercury Management Environmental Impact Statement* (DLA 2004).

Independently of DLA, EPA's Offices of Research and Development (ORD) and Solid Waste (OSW) have been working with DOE to evaluate technologies for permanently stabilizing and disposing of wastes containing mercury (DOE 1999a-1999e; USEPA 2001, 2002a,b). Other comprehensive studies carried out in the recent past include one by SENES Consultants (SENES 2001) who produced a draft report for Environment Canada evaluating 67 technologies for the retirement and long-term storage of mercury. In addition, OSW is considering revisions to the Land Disposal Restrictions (LDRs) for mercury. Land disposal of hazardous wastes containing greater than 260 mg/kg mercury is currently prohibited. For several years OSW has pursued options which would allow land disposal of waste containing greater than 260 mg/kg mercury. These actions include the following:

- Land Disposal Restrictions: Treatment Standards for Mercury-Bearing Hazardous Waste. Notice of Data Availability. Federal Register January 29, 2003 (Volume 68, Page 4481). Presents OSW studies regarding the treatment of elemental mercury and wastes with >260 mg/kg mercury. EPA additionally concludes that changes to national regulations are impractical at this time.
- Hazardous Waste Management System; Identification and Listing of Hazardous Waste; Chlorinated Aliphatics Production Wastes; Land Disposal Restrictions for Newly Identified Wastes; and CERCLA Hazardous Substance Designation and Reportable Quantities. Proposed Rule. Federal Register August 25, 1999 (Volume 64, page 46521). EPA proposed, as an option, an alternative treatment standard for a hazardous waste containing >260 mg/kg mercury which would allow land disposal under certain disposal conditions. This alternative was not ultimately adopted.
- Potential Revisions to the Land Disposal Restrictions Mercury Treatment Standards. Advance notice of proposed rulemaking (ANPRM). Federal Register May 28, 1999 (Volume 64, Pages 28949-28963). This notice presents options, issues, and data relevant to potential revised mercury treatment standards.

At this time, however, no specific revisions to the LDRs for mercury-containing wastes are forthcoming.

Using the above-referenced work as a starting point, EPA prepared report EPA/600/R-03/048, *Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* (USEPA 2002c). In this report, EPA evaluated two types of treatment technologies: sulfide/amalgamation (S/A) techniques and the mercury selenide treatment process. The S/A techniques were represented by: a) DeHg® amalgamation; b) the Sulfur Polymer Solidification/Stabilization (SPSS) process; and c) the Perma-Fix sulfide process. These were grouped as a single class because they have very similar characteristics when compared against the criteria defined by the team (comprised of SAIC staff) and modeled in a computer program that uses the Analytic Hierarchy Process (AHP) as an aid to decision making, Expert Choice. Therefore, only these two general types of treatment technologies were evaluated. These were combined with four disposal options: a) disposal in a RCRA-permitted landfill; b) disposal in a RCRA-permitted monofill; c) disposal in an engineered belowground structure; and d) disposal in a mined cavity. In addition, there were three storage alternatives for elemental mercury: a) storage in an aboveground RCRA- permitted facility; b) storage in a hardened RCRA-permitted structure; and c) storage in a mined cavity.

The purpose of the present work is the logical next step, which is to focus on just a few of the alternatives considered above. This allows a more detailed breakdown and analysis of the stabilization/amalgamation alternatives than was possible in EPA/600/R-03/048, and also allows more effort to be applied to developing cost information.

1.2 Scope of Work

The scope of work requested by EPA was to provide an economic and environmental analysis of the following:

Three treatment technologies, identified as Options A, B, and C to protect certain proprietary information

- Two macroencapsulation alternatives:

  a. Dispose of the treated mercury with macroencapsulation, and
  b. Dispose of the treated mercury without macroencapsulation.

- The alternatives are further divided as follows:

  i. Build a fixed treatment facility at one site to which all of the bulk elemental mercury is transported and dispose of in a collocated monofill, or
  ii. Build a portable waste treatment facility and take it to the sites at which the bulk elemental mercury is stored. Dispose of the treated waste in a centralized monofill.

Combining all the cases above gives 12 alternatives for treatment and disposal[7]. The work includes performing an environmental comparison of these twelve alternatives.

The final part of the work is to develop Life Cycle Cost Estimates (LCCEs)[8] for the foregoing 12 alternatives and the further alternative of storing bulk elemental mercury in an aboveground structure, making 13 alternatives in all. For each of these combinations, SAIC considered alternatives that will treat; a) 5,000 MT; b) 12,000 MT; and c) 25,000 MT of elemental mercury[9]. This gives 39 alternatives for economic analysis.

[7] The authors aware that there are more alternatives than this (e.g., transportation from the centralized treatment site to a remote monofill). However, the authors believe that the extra insights to be gained would not be worth the effort required to keep track of the proliferating alternatives this would generate.

[8] A lifecycle cost estimate is one that provides costs for all elements of a project's lifetime, including preliminary design, final design, startup, operation, and decommissioning.

[9] The basis for selecting 5,000 MT, 12,000 MT, and 25,000 MT was initially that these are multiples of the DLA stockpile numbers. Later EPA analysis (Randall 2005) estimated the quantity of mercury contained in chlor-alkali cells in the US and Western Europe as about 15,000 MT with another 10,000-12,000 MT in the rest of the world. Although opinion varies widely as to the rate at which these cells will close, there is good reason to believe that enough plants will close world-wide within the next 15-20 years to overwhelm dwindling world demand for mercury, thereby posing a question as to its environmentally appropriate disposition.

1.3 <u>Approach</u>

There are three major parts to the required analysis:

- Choice of the three treatment technologies
- Environmental analysis
- Economic analysis

1.3.1 Choice of Three Technologies

The first step was to review the available literature and to hold consultations with EPA personnel in ORD and OSW. This resulted in a short-list of 6 technologies, identified as Options A through F. The references used in this analysis are provided in Section 5.2.

The list was then winnowed down to 3 technologies by using the Kepner-Tregoe decision-making method as a tool. This method is described in Section 2. It essentially involves:

- Developing a list of criteria against which the technologies are ranked
- Assigning a weight to each criterion, on a scale from 1-10, with 10 indicating that the criterion is extremely important and 1 indicating that the criterion is unimportant
- Scoring each technology against each criterion, again on a scale from 1-10, with 10 indicating that the technology performs well against the criterion and 1 indicating that it performs poorly
- For each technology, multiplying the score against a criterion by the weight of that criterion and summing over all criteria. The sums then provide a ranking for the criteria that allows the top 3 to be chosen.

1.3.2 Environmental Analysis

The method chosen for the environmental comparison of the twelve treatment and disposal alternatives is the Analytic Hierarchy Procedure (AHP) as embodied in the Expert Choice software. AHP was developed at the Wharton School of Business by Dr. Thomas Saaty and continues to be a highly regarded and widely used decision-making tool. The AHP engages decision-makers in breaking down a decision into smaller parts, proceeding from the goal to criteria to sub-criteria down to the alternative courses of action. Decision-makers then make simple pairwise comparison judgments throughout the hierarchy to arrive at overall priorities for the alternatives. The decision problem may involve social, political, technical, and economic factors. The AHP helps people cope with the intuitive, the rational and the irrational, and with risk and uncertainty in complex situations. It can be used to: predict likely outcomes, plan projected and desired futures, facilitate group decision making, exercise control over changes in the decision making system, allocate resources, select alternatives, and do cost/benefit comparisons.

The Expert Choice software package incorporates the principles of AHP in an intuitive, graphically based and structured manner so as to be valuable for conceptual and analytical thinkers, novices and subject matter experts. Because the criteria are presented in a hierarchical structure, decision-makers are able drill down to their level of expertise, and apply judgments to the criteria deemed important to their objectives. At the end of the process, decision-makers are fully cognizant of how and why the decision was made, with results that are meaningful and actionable.

In summary, Expert Choice was chosen for the present work for the following reasons:

- It is based on the well-established and widely-used Analytic Hierarchy Process
- It allows the user to incorporate both data and qualitative judgments

- It can be used even in the presence of uncertainties, because it allows users to make subjective judgments
- Once the basic model for a particular decision has been set up, it is easy to perform sensitivity studies
- The model can readily be adjusted as better data become available, or if more alternatives need to be added

The environmental comparison is described in Section 3. Appendix A contains information on the AHP and on how the inputs to the Expert Choice software were specifically developed for the present work. Appendix B contains further detail on the use of the AHP.

1.3.3 Economic Analysis

As described above, 36 treatment and disposal alternatives are being considered. In addition, cost estimates have been prepared for storage of the three masses of elemental mercury in aboveground facilities, making a total of 39 cost estimates in all.

The thirty-six cost estimates (based on the Process Flow Diagrams) for treatment and disposal includes the following elements[10]:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative),
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternatives,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment,
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

The SAIC team developed process flow diagrams for each of the three treatment technologies and the associated macroencapsulation process and a preliminary design for the monofill such that 1,000 MT of elemental mercury will be treated and disposed of each year.

The sources of information for the cost estimates included:

- Published work by the vendors of the three treatment options together with information gathered in telecons. This enabled the team to develop the 1000-MT/year process flow diagrams and to obtain some information on costs.
- Code of Federal Regulation requirements for the construction and operation of a monofill.

[10] Note that these cost do not contain any contingency for the occurrence of accidents or malfunctions (e.g., spillage of elemental mercury during transportation or remediation of excessive leakage from a monofill).

- Standard industry sources of cost information such as Perry and Green's *Industrial Engineering Handbook* and Richardson Engineering Services' *Process Plant Construction Estimating Standards*.
- Telecons with equipment manufacturers.
- Websites of equipment manufacturers.
- The Mercury Management Environmental Impact Statement (MMEIS), published by the Defense Logistics Agency (DLA). This contains detailed information on storage and transportation costs.

The SAIC team assigned uncertainty ranges to items that are input to the total cost. The final cost estimates and uncertainties were estimated by performing an uncertainty analysis using Crystal Ball® software (Decisioneering 2004).

The economic and uncertainty analyses are described in Chapter 4. Appendices C-G provide further detail about cost imputs.

2.0 SELECTION OF TECHNOLOGIES FOR EVALUATION

The contract with EPA required SAIC to consider three different chemical treatment alternatives. The purpose of this chapter is to show how the three alternatives were selected. The chapter describes criteria that were used for this purpose. These criteria were discussed with EPA and represent a consensus.

2.1 Criteria for Selection of Technologies

In the previous project for EPA ORD (*Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury* - USEPA 2002c), criteria were developed when evaluating each potential management alternative (consisting of a treatment technology followed by a disposal method). These criteria included costs, risks, environmental performance, state of maturity, and other factors. The cost criteria and non-cost criteria were given equal importance in the 2002 analysis. Subcriteria were given varying weights based on the evaluation team's consensus. The complete list of criteria used is given in Table 2-1. This list from the 2002 project proved useful as a starting point for identifying important issues for the present project.

Table 2-1. Criteria Chosen for the AHP Analysis in Preliminary Analysis of Alternatives for the Long-Term Management of Excess Mercury, August 2002.

- Non-cost Criteria (0.5)*
  - Compliance with Current Laws and Regulations (0.045)
  - Implementation Considerations (0.154)
    - Volume of waste (0.143)
    - Engineering requirements (0.857)
  - Maturity of the Technology (0.047)
    - State of maturity of the treatment technology (0.500)
    - Expected reliability of the treatment technology (0.500)
  - Risks (0.312)
    - Public risk (0.157)
    - Worker risk (0.594)
    - Susceptibility to terrorism/sabotage (0.249)
  - Environmental Performance (0.336)
    - Discharges during treatment (0.064)
    - Degree of performance testing of the treatment technology (0.122)
    - Stability of conditions in the long term (0.544)
    - Ability to monitor (0.271)
  - Public Perception (0.107)
- Cost Criteria (0.5)
  - Implementation costs (0.5)
  - Operating costs (0.5)

** The figures in parentheses give the weights assigned to each of the criteria and sub-criteria using the process of pairwise comparison that is at the core of the Analytic Hierarchy Process (AHP). At each level, the weights are determined independently and add to one. Higher weights indicate greater importance.*

2.1.1 Identifying Critical Issues

This chapter focuses on the treatment technology step only, prior to further encapsulation and placement of the treated elemental mercury in a monofill. The critical environmental pathway that was evaluated is mercury leaching following disposal. The purpose of the selection process is to identify technologies for further study. Therefore the developed criteria are at a screening level, allowing for more detailed review later in the process.

The proposed issues are presented in Table 2-2. The following six issues are identified:

1. Appropriateness of technology for the treatment of elemental mercury
2. Type of leaching performance data
3. Results of leaching performance tests
4. Extent of environmental and cost information
5. Costs and Complexity
6. Development

Each of these issues is assigned a weighting factor of between 1 and 10 to account for its perceived importance. Table 2-2 provides the consensus suggestions for these weighting factors. The first three issues are assigned a weighting factor of 10, reflecting the team's view that the ability to treat elemental mercury with the end product having satisfactory leaching performance is the primary objective of the technology. Having adequate information about environmental performance and costs is deemed relatively important (a weight of 8), otherwise it is hard to perform a credible analysis of the technology. Finally, expected costs and the current state of development are deemed somewhat less important because these issues can potentially be worked on and improved over time.

2.1.2 Evaluation of the Technologies

One important aspect of the evaluation is to identify any 'pass/ fail' criteria for a particular issue. For example, if a particular technology fails to meet some minimum criterion, then the technology would be dropped from consideration. An example of such a criterion is included in the first row of Table 2-2, where the technologies, at a minimum, should at least in theory be capable of treating elemental mercury.

An additional aspect is the effectiveness with which each technology addresses each issue. This aspect is addressed by providing a score, as is laid out in Table 2-2. Like the issue weighting factors, the score ranges from 1 – 10.[11] For each issue, the score for a particular technology is multiplied by the weight. This product is then summed over all issues to give a total score for the technology. This method of ranking technologies is known as Kepner-Tregoe Decision Analysis.

2.1.3 Identifying Candidate Processes

Many treatment processes are available for reducing the mobility of mercury in various wastes. However, only a small number of these are expected to be practical for elemental mercury treatment. It is possible to evaluate any number of candidate treatment processes using the criteria in Table 2-2. To avoid inefficient research into technologies that are impractical or only marginal in meeting the project objectives, the following types of technologies were excluded from the evaluation:

- Mercury recovery or extraction technologies, where the intent is to remove or separate the mercury from a waste for recycling or further treatment

[11] For some issues, the scoring process outlined in Table 2-2 allows a score of greater than 10. In this case, the score is capped at 10. Similarly, there is the possibility that some scores can be zero or negative. In this case, the score is not allowed to fall below 1.

- Technologies which treat wastewaters or combustion exhaust gases
- Technologies which focus on the treatment of LDR "low mercury" wastes (i.e., less than 260 mg/kg total mercury)

Six technologies were identified as having been used for treating wastes with, at a minimum, percent levels of mercury. They are identified as Options A through F. References used for this part of the analysis are listed in Section 5.2.

Any number of additional treatment technologies can in principle be evaluated.

2.2 Scoring Results

The resulting scores for each technology with respect to each criterion are presented in Table 2-3. The following subsections discuss the information that forms the basis for the scoring results presented in Table 2-3.

2.2.1 Option A

The Option A process was one of three technologies evaluated by EPA for elemental mercury treatment, in which leaching was evaluated with respect to pH in oxidizing conditions (see Figure B-1). Other available data for the treatment performance of elemental mercury includes TCLP and ASTM testing by the developer of the technology . Several other treatment performance results are available for mercury wastes, including work in which mercury leaching as a function of pH and liquid-solid ratio was investigated.

Data are available regarding the formation of mercuric sulfide under long-term conditions; these data are not specific to any particular technology but can potentially be useful for sulfur-based treatment processes in general. For example, as discussed in Appendix B, mercuric sulfide (HgS) production may degrade to from HgS2 anion under alkaline anaerobic conditions. One potential application of the result is that such conditions would favor the transformation of residual elemental mercury to this stable form. An alternative application is that in an anaerobic monofill in damp or wet conditions, ionic mercury (Hg+) and/or ionic mercury bisulfide (HgS2=) may form and result in increased leaching over time.

In the EPA study for elemental mercury treatment, OSW identified highly variable leaching as a function of pH (as shown in Figure B-1 of Appendix B); laboratory quality control checks suggest the reported data are valid (EPA, 2002b). The results suggest the inherent uncertainties of using a relatively small set of studies to identify if the observed results represent actual performance of the treatment process or are a result of heterogeneity in the treated waste, treatment variation, or other factors. This uncertainty is equally relevant for Technology Options B and C.

The Option A process remains in active development. It has been demonstrated at pilot-scale on liter quantities of mixed-waste elemental Hg from National Laboratories, and in treatability studies for a major gold-mining corporation (Randall 2005). After this corporation conducted its own evaluation, it selected Vendor A for potential treatment of its by-product elemental Hg from foreign mining operations, and has licensed the technology. There are also plans to build a process facility in Kazakhstan that will treat elemental mercury and mercury-contaminated soil. Therefore, it appears that technology A is approaching commercial-scale operation.

2.2.2 Option B

Information available for the Option B process closely parallels that available for Option A. The treatment of elemental mercury was evaluated by EPA; TCLP testing of treated elemental mercury was conducted by DOE. In addition, existing general mercuric sulfide formation data can similarly be applied to the sulfur-based Option B technology.

USEPA data show a trend in leaching results with respect to pH, with results lowest in acidic conditions and highest in basic conditions (see Figure B-1). The results were consistently below the UTS level at all but the highest range of pH.

The Option B process has been used for the treatment of approximately 7600 kg (3.5 tons) of radioactive elemental mercury since 2001. Therefore the process is in active use and development.

2.2.3 Option C

Information available for the Option C process includes elemental mercury treatment data by USEPA and DOE TCLP testing of treated elemental mercury. The Option C process was also used for the experimental treatment of mercury-containing soil in DOE's MER-03 program, where mercury leaching as a function of pH and liquid-solid ratio was investigated.

The USEPA data shows a trend in leaching results with respect to pH, with the lowest leachable levels present in basic conditions (see Figure B-1). At pH levels above 6, the mercury solubility was between the UTS and TC levels.

There is no indication of commercial use beyond bench-scale treatment, although the Option C process remains in active development/ sponsorship.

2.2.4 Option D

Option D is a selenide process, for which very little environmental data are available.. USEPA investigated the leaching of mercury selenide with respect to pH and chloride anion concentrations, although testing was conducted only on a simulated waste treatment residual. The process was developed for the vapor-phase treatment of elemental mercury generated from lamps, batteries, etc.; it could likely be adapted to a starting point for elemental mercury.

This process is in commercial use in Europe, making it one of the few treatment processes in use at larger than bench scale. However, the scale of the equipment is expected to be small relative to the quantities of mercury present in the DLA stockpile (for example). The process is also relatively complex due to the high temperatures and continuous processing.

2.2.5 Option E

Option E uses a dithiocarbonate formulation and a small amount of proprietary liquid to produce a stabilized waste form. This technology has the disadvantage of not having been applied to elemental mercury. Numerous applications of the technology have been conducted in the DOE MER programs where percent levels of mercury in wastes were tested. Its potential application to elemental mercury, therefore, is unknown.

EPA studies have shown that the leachable mercury concentrations were consistently above the UTS level for most of the pH range. The MER-03 study results are consistent in that the mercury solubility was found to be lowest at the alkaline pH levels.

The development status of the Option E process is not known.

2.2.6 Option F

Sulfur-impregnated activated carbon has been used for many years in the cleanup of mercury-contaminated flue gas. However, only limited information is available with regard to how such a material may treat mercury-containing wastes. Only limited results are available for the testing of a simulated mercury-contaminated soil. Its potential application towards elemental mercury is unknown.

Available data show a wide range of testing with respect to leaching variables including pH and chloride content of the leaching solution. In addition, an additional treatment step of cement stabilization is conducted following activated carbon treatment in some cases. The leachable mercury concentrations were consistently below the UTS level for pH 4 and above.

This technology remains in the research stage. However, it is based on the use of readily available materials. In addition, use/ research for mercury removal from flue gas can be transferred to solid waste applications.

2.3 Conclusions

The results of the scoring are presented in Table 2-3. Three technologies (Options A, B, and C) have similar scores. The remaining three technologies (Options D, E, and F) also have similar scores but significantly lower than the other three technologies. These results support the choice of the Options A, B, and C processes for more detailed evaluation.

Table 2-2. Elemental Mercury Treatment Technology Evaluation

Proposed Issue	Weighting Factor (1-10) for Issue	Proposed Evaluation Criteria and Scores for Each Technology	Minimum Acceptable Result (if any)
Appropriateness of technology for the treatment of elemental mercury	10	10 – The technology has been tested on elemental mercury (100%) 6 – The technology has been tested on mercury-containing wastes/ soils with percent levels of *elemental* mercury 5 – The technology has been tested on mercury-containing wastes/ soils with percent levels of *any form of* mercury 1 – The technology has been tested only on low mercury content wastes (e.g., <260 mg/kg)	The technology should be applicable to elemental mercury treatment, at least in theory.
Type of leaching performance data	10	Points for each of the following (maximum 10 points): + 1 point – TCLP (or similar) testing has been conducted + 2 points – leaching as a function of pH variation + 2 points – leaching as a function of liquid/ solid ratio + 2 points – long-term stability testing + 2 points – leaching in various oxidation/ reduction conditions + 1 point – leaching in the presence of various anions	None
Results of leaching performance tests	10	Results of leaching performance tests (maximum score 10 points; minimum 1 point): -2 points to +2 points – Extent to which data trends (if any) are logical, and results for sample duplicates give reasonable results. -2 points to +2 points – Extent to which sampling and analysis procedures are well documented and minimize possible errors - 1 points to + 5 points – For conditions which may be encountered in a monofill (e.g., pH), the leaching results are (1) below universal treatment standards (UTS) in most relevant conditions (+ 5 points); (2) some results are above UTS but still below the TC (+ 2 points); (3) results are higher than the TC level in critical instances (- 1 point). + 1 point – Where two or more studies are available, contradictory findings are not reached.	None

Table 2-2. Elemental Mercury Treatment Technology Evaluation (continued)

Proposed Issue	Weighting Factor (1-10) for Issue	Proposed Evaluation Criteria and Scores for Each Technology	Minimum Acceptable Result (if any)
Results of leaching performance tests	10	Results of leaching performance tests (maximum score 10 points; minimum 1 point): -2 points to +2 points – Extent to which data trends (if any) are logical, and results for sample duplicates give reasonable results. -2 points to +2 points – Extent to which sampling and analysis procedures are well documented and minimize possible errors - 1 points to + 5 points – For conditions which may be encountered in a monofill (e.g., pH), the leaching results are (1) below universal treatment standards (UTS) in most relevant conditions (+ 5 points); (2) some results are above UTS but still below the TC (+ 2 points); (3) results are higher than the TC level in critical instances (- 1 point). + 1 point – Where two or more studies are available, contradictory findings are not reached.	None
Extent of environmental and cost information	8	Extent of environmental and cost information (maximum score 10 points): + 2 points – Data available from multiple sources (e.g., vendor test, EPA). + 2 points – One or more EPA/ DOE test documents (e.g., MER program) + 1 point – If not evaluated in the MER program, information is available from the DLA EIS + 2 point – Patents, conference papers, and/or journal articles + 1 point – If no patents, etc., then other product literature is available. + 2 points – Information on both costs and environmental performance are available from resources + 2 points – Process information is available to verify/ expand the cost data + 1 point – General treatment information is available (e.g., sulfide or selenide chemistry) which is not technology specific, but still useful. - 1 point – Critical information is not in English.	None
Costs and Complexity	5	10 – Costs and Complexity are expected to be significantly lower than typical (non-mercury) hazardous waste stabilization/ solidification (S/S) processes 5 – Costs and Complexity are expected to be about the same as typical hazardous waste S/S processes. 1 – Costs and Complexity are expected to be significantly higher than typical hazardous waste S/S processes.	None
Level of Development of Technology	5	10 – The technology is actively in use for mercury treatment/ disposal at a scale which would be practical for treating >5,000 tons 5 – The technology remains in the testing/ development stage by a sponsoring organization 3 – The development status is not known 1 – The technology has been developed but no present sponsor is evident	Must be capable of commercial deployment in the future

Table 2-3. Elemental Mercury Treatment Technology Evaluation

Proposed Issue	Weighting Factor (WF)	Preliminary Result (score between 1 and 10) for Technology Type; Multiply by Weighting Factor to Obtain Score for Each Issue					
		Option A	Option B	Option C	Option D	Option E	Option F
Appropriateness of technology for the treatment of elemental mercury	10	10 x WF = 100	10 x WF = 100	10 x WF = 100	9 x WF = 90	5 x WF = 50	5 x WF = 50
Availability of leaching performance data	10	6 x WF = 60	4 x WF = 40	5 x WF = 50	3 x WF = 30	5 x WF = 50	5 x WF = 50
Results of leaching performance tests	10	2 x WF = 20	7 x WF = 70	5 x WF = 50	3 x WF = 30	4 x WF = 40	4 x WF = 40
Extent of environmental and cost information	8	10 x WF = 80	6 x WF = 48	6 x WF = 48	3 x WF = 24	5 x WF = 40	4 x WF = 32
Costs and Complexity	5	5 x WF = 25	5 x WF = 25	5 x WF = 25	2 x WF = 10	5 x WF = 25	5 x WF = 25
Development	5	8 x WF = 40	5 x WF = 25	5 x WF = 25	8 x WF = 40	3 x WF = 15	6 x WF = 30
Final Score		325	308	298	224	220	227

3.0 ENVIRONMENTAL ANALYSIS USING THE ANALYTIC HIERARCHY PROCESS

3.1 Finalized List of Alternatives

This is the finalized list of treatment alternatives for both the environmental analysis (using the Analytic Hierarchy Process (AHP)) and the cost analysis (see Chapter 4). A description of the AHP is included in Appendix A.

1. Option A+no macroencapsulation+centralized treatment
2. Option A+no macroencapsulation+mobile treatment
3. Option A+macroencapsulation+centralized treatment
4. Option A+macroencapsulation+mobile treatment
5. Option B+no macroencapsulation+centralized treatment
6. Option B+no macroencapsulation+mobile
7. Option B+macroencapsulation+centralized treatment
8. Option B+macroencapsulation+mobile treatment
9. Option C+no macroencapsulation+centralized treatment
10. Option C+no macroencapsulation+mobile treatment
11. Option C+macroencapsulation+centralized treatment
12. Option C+macroencapsulation+mobile treatment

3.2 Assumptions and Ground Rules

The first stages of the analytic hierarchy process were carried out in a brainstorming meeting in June 2004 involving both EPA and SAIC personnel. To assist in the process, all participants discussed and agreed to some ground rules, as follows:

- The intent of the AHP is to address environmental effects, not costs. An economic analysis of the twelve alternatives was performed after completion of the AHP and is described in Chapter 4.
- Since there are twelve alternatives, the effort required to pairwise compare these against each AHP criterion[12] would be excessive - 12x11/2= 66 pairwise comparisons per criterion. Therefore, the team instead defined a range of "intensities" for each criterion[13].
- The environmental ranking arising from the AHP exercise is not sensitive to the total mass of mercury (5,000, 12,000, or 25,000 tons). Therefore, there is no need to specify a mass for the AHP[14].
- "No macroencapsulation" means that the stabilized waste will be placed in the monofill exactly as it is generated by the stabilization process. If the process ends with the waste solidifying in some form of container, this container will be given no credit for reducing the rate of leaching.
- "Macroencapsulation in the best available medium" means macroencapsulation in a separate step after stabilization. It was agreed that, for the purposes of both the AHP and the cost analyses, the macroencapsulation technology will be the ARROW-PAK system, in which waste is sealed in polyethylene containers prior to disposition in a monofill. The already-formed polyethylene containers will be purchased from the manufacturers and filled and sealed at the stabilization site.

[12] See Appendix A for an explanation of AHP criteria.
[13] See also Appendix A for an explanation of AHP intensities.
[14] There was some discussion about whether the mass of mercury might affect some of the criteria (e.g., higher transportation risks for higher quantities), but this would not influence the rankings because all options would be affected the same way.

The ARROW-PAK system is expected to be available in a variety of sizes; the cost and environmental analyses will incorporate appropriate assumptions for container size[15].

- While many elements of the design and construction of the monofill will be independent of the disposal alternatives, there might be some features that are technology dependent, such as the composition of the liner and adjustments to the fill material to maintain pH. As discussed in Appendix B, lime can be added to maintain (or promote) basic conditions and sulfur can be added to maintain (or promote) acidic conditions, although many other soil and environmental conditions will influence the ability of the monofill to maintain these pH conditions.

3.3 AHP Brainstorming Session

The EPA/SAIC brainstorming team defined a goal, developed criteria and subcriteria, and assigned a range of intensities to each subcriterion.

3.3.1 The Goal

The goal is simply stated: "Minimize environmental impact during life cycle." Having this goal helps the project team keep focused.

3.3.2 Development of Criteria and Subcriteria

The team brainstormed a list of criteria and subcriteria that they considered to be potential discriminators among the twelve options in terms of environmental performance. Those criteria and subcriteria are listed in Table 3-1.

3.3.3 Pairwise Comparison to Rank the Criteria and Subcriteria

The team pairwise compared each of the criteria, and then each of the subcriteria, in order to develop weights that are intended to be a measure of the relative importance of each criterion and subcriterion. The Expert Choice matrices for criteria and subcriteria are shown in Table 3-2. The resulting weights, as calculated by Expert Choice software, are summarized in Table 3-1.

3.3.4 Development of "Intensities" for each Criterion and Subcriterion

As noted above, there are 12 alternatives. In principle, each of these should be pairwise-compared against each of the criteria or subcriteria, leading to the need to perform 10 criteria x (12x11/2) = 660 pairwise comparisons. This is a rather large number (e.g., one comparison per minute would take 11 brainstorming hours), so the team decided to use an optional AHP technique whereby the criteria are first assigned "intensities." These intensities are summarized in Table 3-1. As can be seen, these are quite simple, most of them simply being "low," "medium," or "high." "Low" should be taken as meaning "low potential impact on the environment," etc., so that "low" is always the most desirable outcome.

For the two subcriteria that are not allocated low, medium, or high intensities, one (the possibility of mercury spills during transportation) is simply allocated two intensities – either a mercury spill is not possible ("no," the most desirable situation), or a mercury spill is possible ("yes").[16] The other (the

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[15] The fact that the ARROW–PAK technology was used in the present work does not mean that EPA endorses it as the best available macroencapsulation process.

[16] The simplicity of the intensities for the possible spillage of mercury during transportation is made possible because of a simplifying assumption that was made in SAIC's original proposal. Either elemental mercury is treated at a centralized stabilization facility and disposed of in a collocated monofill, in which case elemental mercury is transported to the treatment location and could hypothetically be spilled en route: or mobile treatment facilities are sent to the current storage locations and

possibility of spills of stabilized waste during transportation) is assigned three intensities ("none," transportation of "encapsulated" waste, and transportation of "non-encapsulated" waste.

In order to convert each assignment of intensities into a score or weight that can be used in Expert Choice's ultimate calculation of the relative ranking of technologies, the team pairwise-compared the intensities, as is summarized in the last column of Table 3-1.

The next step is to assign each alternative an intensity with respect to each criterion or subcriterion. Thus, each alternative needs ten intensity assignments and there are 120 such assignments in total. The team decided that they did not have enough knowledge at their fingertips to make these assignments. Instead, the team identified factors and phenomena that need to be evaluated before deciding on the intensity assignments. These factors are listed in Appendix B. After the brainstorming meeting, SAIC gathered relevant information and made intensity assignments that were subsequently reviewed by the EPA team. The basis for assigning the intensities is also discussed in Appendix B. This allowed Expert Choice to be run so as to provide a baseline ranking of the twelve alternatives.

3.3.5 Assignment of Intensities to Alternatives

The results from Appendix B are summarized in Table 3-3. Appendix B describes in detail the available data and the assignment of these intensities. As shown in Table 3-1, the assignment of intensities for monofill disposal has a significant affect on results; information below is included to further describe the data and limitations of information relevant to this particular criterion. As detailed in Appendix B, factors included consideration of volatilization, presence of favorable pH conditions, long-term stability of the waste, and long-term stability of the encapsulating material (if present).

Available data suggest that each of the technologies appear to perform best in different environmental conditions (e.g., acidic or basic conditions). The alternatives were evaluated based on the conditions expected to result in the lowest leachate concentrations, although as discussed previously land disposal of treated elemental mercury is currently prohibited and therefore comparison of results to other regulatory levels (e.g., UTS levels) is of interest but not as important as identifying the optimal range of disposal conditions for each technology.

One benefit of macroencapsulation is to act as a barrier against disposal conditions which may increase mobility of mercury from the treated waste. For example, all of the wastes leach mercury at different pH. If landfill conditions deviate from the 'optimal' conditions suggested by available data, then a waste without macroencapsulation would be expected to leach higher amounts of mercury than a macroencapsulated one.

There is considerable uncertainty with regard to leaching performance over the long term. For example, as discussed in Appendix B, mercuric sulfide (HgS) production is favored under alkaline anaerobic conditions. One potential application of the result is that such conditions would favor the transformation of residual elemental mercury to this stable form. An alternative application is that in an anaerobic monofill in damp or wet conditions, ionic mercury (Hg+) and/or ionic mercury bisulfide (HgS2=) may form and result in increased leaching over time.

In addition, incomplete data are available for many factors which affect leaching, such as pH buffering capacity, or performance under conditions as a function of oxidizing/ reduction conditions (i.e., aerobic/ anaerobic).

3.4 Results of the Baseline Expert Choice Analysis

The 12 alternatives identified in Section 3.1 above were evaluated using the Expert Choice software. The data from Tables 3-1 and 3-3 were used as inputs to the model. While the input to the model is

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elemental mercury is stabilized there, so that elemental mercury will not be transported and there is no chance of a spill. It is recognized that the real world situation may involve some transportation of both elemental mercury and of treated waste.

somewhat narrative (e.g., intensities such as ‘low,’ ‘medium,’ and ‘high’), the output provides a single numerical result for each alternative.

To interpret the results, it is important to note that no alternative will achieve a ‘perfect score,’ however defined. This is because the alternatives are evaluated partially against each other, so that the total score will always equal unity no matter how many alternatives are evaluated. In addition, as the number of alternatives increases or decreases, the score of each alternative will change to maintain the same sum of scores of all alternatives (i.e., unity). In this manner, the results are best interpreted as scores *relative* to each other, rather than the *absolute* value of an alternative’s score.

Table 3-4 presents the Expert Choice results for each of the twelve alternatives discussed in the previous section of this report. The table shows the score, and corresponding ranking, of each alternative when considering all criteria. The results from the model were multiplied by 1,000 for convenience to provide a score as a whole number, rather than as a decimal.

The following are some observations from Table 3-4:

- In general, mobile treatment alternatives score better than centralized treatment alternatives.
- There is a slight preference for macroencapsulation alternatives over alternatives which do not include this additional treatment.
- All of the alternatives that include Option B technology score higher than alternatives that include Option C technology. Alternatives that include Option A technology are more scattered; one Option A alternative scores highest while a different Option A alternative scores lowest.

Several additional analyses were conducted to explain or confirm these results. First, the team evaluated whether results were reasonable based on the preferences and intensities assigned above. Second, the team conducted additional sensitivity and uncertainty analyses with the Expert Choice software to identify how changes in the preferences and intensities affect the rankings in Table 3-4. The results of the sensitivity and uncertainty analyses are presented in Section 3-7. The reasonableness of the above three conclusions derived from analysis of the AHP model output - is evaluated below (Sections 3.6.1 – 3.6.3.)

Another important consideration is the difference between the results for each alternative. It must be determined if the magnitudes of these differences are large enough to be significant, or whether the results indicate that the numerical results are similar. In general, small differences between one alternative and another indicate that no discernible difference exists between the two. A determination of what is ‘small’ is addressed primarily through the sensitivity and uncertainty analyses, as identified in Section 3.7. In general, differences of 5 to 10 points out of 1000 can easily result from small changes in the intensities or weightings, and therefore such differences between various alternatives are not expected to be significant.

3.4.1 Factors Which Influence the Scoring of Mobile Treatment Versus Centralized Treatment Alternatives

Table 3-3 shows that transportation factors differ significantly between mobile and centralized treatment alternatives. In other words, the greatest differences in intensities between mobile and centralized treatment alternatives result from two of the three transportation factors (transport of mercury and transport of waste). As shown in Table 3-1, transportation factors (particularly the transport of mercury) significantly affect the scoring.

As explained previously, for all alternatives involving mobile treatment there is no transport of elemental mercury, but there is transport of treated waste. The importance of these differences in intensities is shown in Table 3-1, which shows that concerns about the transport of elemental mercury (0.747) are much higher than concerns about the transport of treated waste (0.119). In addition, Table 3-1 shows that the potential environmental impacts during the transportation phase of the mercury lifecycle were determined to be the second-most important criterion (i.e., the weight of 0.216 is the second-highest weight).

In summary, Tables 3-1 and 3-3 shows that it is reasonable to expect mobile treatment alternatives to score higher than do centralized treatment alternatives, all other things being equal. This is because, by assumption, there is no transport of elemental mercury associated with the mobile treatment alternatives whereas, in the centralized treatment alternatives, all of the elemental mercury is transported to a centralized treatment facility. The Team determined that potential impacts of elemental mercury spills during transportation represent a significant potential risk, which should be minimized.

As discussed in Section 3.3.4, there is some simplification of the mobile and centralized treatment alternatives. Mobile treatment is assumed to occur at a location with a fairly sizable quantity of mercury, such as a DLA stockpile site, a chlor-alkali facility, or a mercury waste recovery facility. In the first two examples, there will be no transport of elemental mercury (i.e., the mercury is already at the site). In the third example, relatively small quantities of elemental mercury or mercury-containing wastes (e.g., thermometers) are sent by individual generators to a mercury recovery facility, and the recovered elemental mercury is assumed to be treated without further transport. Therefore, the mobile treatment alternatives as evaluated by the project team do not completely account for all movements of mercury, although the transportation of these smaller shipments likely will be required regardless of whether treatment occurs in a centralized location or a mobile location.

3.4.2 Factors Which Influence the Scoring of Macroencapsulation Versus Non-Macroencapsulation Alternatives

Table 3-3 can again be used to identify the factors that significantly affect the scoring for macroencapsulation and non-macroencapsulation alternatives. These occur with the transportation of treated waste (i.e., for mobile treatment alternatives), and for the short-term disposal of treated mercury in the monofill for two of the three treatment technologies (i.e., Options A and B). For each of these criteria, macroencapsulation results in reduced risk versus non-macroencapsulation. In particular, Table 3-1 shows that potential environmental impacts during the disposal phase of the mercury lifecycle were determined to be the most important criterion (i.e., 0.493 is the highest weight), showing that differences in intensities associated with this criterion are expected to be very important. As shown in Table 3-3, differences in the macroencapsulation options result in different intensities for the short term (<40 years) and/or long term (>40 years) disposal. Appendix B identifies how these intensities were assigned.

Because macroencapsulation is primarily intended to reduce risks in the disposal phase, it is reasonable to expect that these alternatives score higher than do alternatives that do not incorporate macroencapsulation.

3.4.3 Factors Which Influence the Scoring of the Three Technology Options

There was significant scattering between each of the four alternatives associated with the Option A technology, while there was a certain amount of clustering associated with the other two technologies. Table 3-3 assists in explaining the results for the Option B and Option C technologies. Table 3-3 shows that all six alternatives (including all four Option C alternatives) with an intensity of 'Moderate' for long-term (>40 year) monofill stability have the lowest scores. As suggested by these results, and verified in the uncertainty analysis (Section 3.7), the assigned intensity of this criterion is a principal factor in the overall score for these six technologies. All four Option B alternatives have an intensity of 'Low' for this criterion.

With respect to Option A, the results suggest that the technology has advantages and drawbacks, which somewhat complicates the trends. It also suggests that other major differences between the alternatives (i.e., centralized versus mobile treatment, and macroencapsulation versus non-macroencapsulation) significantly affect the score for the Option A alternatives.

3.5 Sensitivity and Uncertainty Analyses

Both sensitivity analyses and uncertainty analyses were conducted using the Expert Choice software. These analyses served two functions: (1) to provide insight into how the overall scores were generated, and (2) to identify how changes in the emphasis or intensities of different criteria would influence the results. For this analysis, sensitivity refers to changes in emphasis of the different criteria (e.g., the five first-level criteria identified in Table 3-1). Uncertainty refers to changes in the assignments of the intensities (e.g., the values identified in Table 3-3). No analyses were conducted which changed the overall structure of the model (e.g., adding new criteria).

3.5.1 Sensitivity Analyses

A sensitivity analysis is a type of 'what-if?' analysis. The intent is to identify how the results would change if a particular criterion was deemed to be more (or less) important than that considered in the baseline analysis results of Table 3-4. In particular, the sensitivity analysis changed the weights of each of the five first-level criteria identified in Table 3-1. These changes were considered as follows:

- Changing the weight of the final disposal criterion from 49.3% to 75% (i.e., more important)
- Changing the weight of the final disposal criterion from 49.3% to 25% (i.e., less important)
- Changing the weight of the transportation criterion from 21.6% to 40% (i.e., more important)
- Changing the weight of the transportation criterion from 21.6% to 10% (i.e., less important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 40% (i.e., more important)
- Changing the weight of the abnormal/ accidental operations criterion from 18.8% to 10% (i.e., less important)
- Changing the weight of the routine operations criterion from 6.5% to 13% (i.e., more important)
- Changing the weight of the routine operations criterion from 6.5% to 3.2% (i.e., less important)
- Changing the weight of the decommissioning criterion from 3.8% to 7.6% (i.e., more important)
- Changing the weight of the decommissioning criterion from 3.8% to 1.8% (i.e., less important)

In making these changes, the importance of each of the other four criteria was reduced proportionally so that the contributions from all six criteria add to 100 percent. The sensitivity analysis results of the three most sensitive criteria, which are the first six bullets listed above, are summarized in Table 3-5. The remaining sensitivities are presented in Appendix A and make very small differences to the scores.

The sensitivity analysis considered large, but not extreme, changes in the weights of the first-level criteria. The first column of results in Table 3-5, labeled 'baseline,' corresponds to the results in Table 3-4. In this column, the importance of each of the five criteria is equal to the percentages listed in Table 3-1 (e.g., transportation is 21.6%). The next columns list the sensitivity results for each of the first six of the ten scenarios identified above. For example, for the transportation (high importance) sensitivity analysis, the contribution of this criterion to the importance of all non-cost criteria was moved from 21.6% (i.e., the 'baseline' reflected in the first results column) to 40% (+/- 0.2%). The importance of each of the other four first-level criteria was reduced proportionally so that the contributions from all five criteria add to 100 percent.

Some specific observations include the following:

- As shown in Table 3-5, the same two alternatives remained the highest for both the baseline analysis and the six sensitivity analyses (i.e., Option A and Option B with mobile treatment and macroencapsulation). At the other extreme, the same single alternative remained the lowest in all cases (i.e., Option A with centralized treatment and no macroencapsulation). This helps show the stability in the results. Even as the weightings are changed over a wide range, both the rankings and the absolute scores change in predicable ways.
- The baseline score is in between the extremes of the range for each alternative, again validating the general model performance. For example, for the first row in Table 3-5, when evaluating potential risks from transportation, the alternative score moves from 115 (for low importance) to 120 (for high importance). A score of 117 (the baseline) is achieved when the weighting is midway between these extremes.
- The rank of each alternative is unchanged from the baseline when evaluating the potential for accidents from operations, routine operations, and decommissioning. This suggests that the alternatives are not sensitive to these criteria using the assigned intensities.

3.5.2 Uncertainty Analyses

Uncertainty identifies the extent to which variation in the information and data influences appropriate conclusions. An uncertainty analysis is conducted to assess confidence in the results. In this section of the report, uncertainty is incorporated into the analysis by using (1) ranges of available information and data, and (2) 'what-if' analyses for cases in which the true range is unknown or not well defined. For example, a different calculation, or assessment, is generated for values associated with the extreme of a range.

This section of the analysis discusses some of the sources of uncertainty identified in Appendix B that are expected to impact the results and demonstrate their effect for selected alternatives. These areas of uncertainty include the following:

- Monofill Disposal Stability for Option C- long term: Conflicting data are available regarding the degree of mercury vapor generation from the Option C process, which is an area of uncertainty affecting stability. This issue is discussed in more detail in Section 3.8.
- Monofill Disposal Stability for Option A: As discussed above, a single alternative scored lowest in all sensitivity analyses (i.e., centralized treatment of Option A with no macroencapsulation). As an uncertainty analysis, intensity values of this alternative were changed to demonstrate how its score may rise.
- Other Monofill Disposal Stability: An obvious area of uncertainty for all alternatives is the degree to which the disposal conditions will remain stable for both a short and a long period of time (less than 40 years and greater than 40 years, respectively). This range is demonstrated for one of the alternatives. In addition, the scale-up performance of the treatment technologies themselves is uncertain with regard to their ability to treat relatively large quantities of mercury for an extended period of time.
- Accidental Releases of Mercury During Operations: Risks of accidental releases of mercury during the mercury treatment step may be higher or lower than evaluated. This range is demonstrated for two of the alternatives.

A series of different analyses were conducted using the Expert Choice software for several of the selected alternatives to better identify the impact that uncertainty has on the results. These analyses and results are described in Table 3-6. Each row of the table represents an instance where data are changed for just one of the alternatives. As shown, a total of 11 different uncertainty analyses were conducted.

The 11 sets of uncertainty analysis results in Table 3-6 show how the overall ranking of each alternative is affected as the intensities of individual criteria are changed. These uncertainty analyses show that results change most significantly in the case of changing the intensity of the long term (>40 year) disposal criterion between 'Moderate' and 'Low.' This is shown for Reference Nos. 1 through 7. For example, the lowest-scored Option A alternative in Table 3-4 (Reference No. 3) significantly improves its score, from 48 (12^{th} best) to 84 (6^{th} best). Changes in the intensity of the shorter term (<40 year) value also improve the score, but not as much (Reference Nos. 2 and 4).

Uncertainty with regard to accidental releases (mercury spills) during operations have a relatively small effect on results. For example, an Option B alternative (Reference Nos. 8 and 9) still ranks high regardless of whether the intensity is given a value of low, moderate, or high.

The uncertainty analysis can be used to identify important parameters in which further research may be required. That is, particular attention could be placed on uncertain data, which significantly affect the results. As shown above, this suggests that uncertainty with regard to long-term storage and disposal represents one such parameter.

Further uncertainty analyses can take into account potential simultaneous variations in all of the values that are input to the Expert Choice calculation. This can in principle be done by using Monte-Carlo-based techniques. This was not feasible in the course of the present work.

3.6 Release Rates of Mercury

This section presents the results of a preliminary estimate of the quantity of mercury which may be released from monofill disposal. Mercury may be released as a result of leaching and volatilization mechanisms. For this preliminary analysis, the leachate concentration is multiplied by estimates of the infiltration rate and the landfill area (i.e., the leachate volume) to estimate a leaching release rate. Similarly, the quantity of mercury lost to volatilization is estimated to be equal to the quantity of landfill gas generated multiplied by the gas concentration. The resultant estimates are intended to provide a range reflective of uncertainty, and are based on simplified approaches to the actual physical mechanisms.

As shown in Figure B-1, the quantity of mercury present in leachate is dependent on site-specific environmental conditions such as pH; such conditions may vary over time. The results of Figure B-1 were used as a guide in estimating the range of mercury concentration. Specifically, a lower bound of leachate concentration for each of the three technologies is generally at or slightly below the universal treatment standard (UTS) of 0.025 mg/L. For this analysis, a lower bound of 0.01 mg/L and an upper bound of 1 mg/L are used. This wide range of concentration is intended, in part, to represent a range of uncertainty. In practice, the actual concentrations may even be outside this range.

The results of a study (Wong, 1997) of four Florida landfills capped with synthetic liners were used to estimate infiltration; the hypothetical mercury waste monofills also have synthetic liners and using a report such as Wong (1997) simplifies the analysis by avoiding the need for site-specific modeling. This is intended to provide an order-of-magnitude result, because these parameters may also change over time particularly due to (1) differences in waste properties and (2) the quantity of water entering the monofill, which is typically not equal to the quantity of leachate leaving the monofill due to unsteady-state conditions. Based on Wong (1997), it is assumed that 5% of the rainfall infiltrates through the liner. For the above reasons, there is variability associated with this percentage.

The sizes of the monofills are based on data presented in Appendices E through G of this report.

The sizes of the monofills are dependent on the technology type and whether or not the waste is encapsulated; rather than evaluating each case separately an upper and lower end of the range is provided for each waste quantity.

The quantity of mercury released (volatilized) is a function of the gas generation rate and the mercury concentration. No data are available for gas generation rates from hazardous waste landfills; rather, a great deal of information is available for municipal solid waste landfills (MSWLs) (AP-42; EPA 1998). These MSW rates were used as a bounding estimate, as release rates for the case of a mercury monofill are expected to be much less because of the absence of mechanisms available which would generate landfill gas. The concentration of mercury in the gases is based on the volatilization data in Appendix B with the upper bound corresponding to untreated elemental mercury.

Table 3-7 summarizes the results for both volatilization and leachate release mechanisms. Table 3-7 shows ranges of leachate generation in the range of <1 to 1,500 g/yr and ranges of volatilization in the range of 1 to 1,000 g/yr. These compare to the following data:

- The Swedish EPA (2003) has set a goal of 0.5 to 10 grams per year mercury for the leaching of mercury waste in a deep rock repository. This goal is based on the assumption that the mercury will have localized effects to fish at a hypothetical small lake. The Swedish EPA goals represent the leaching pathway. The values in Table 3-7 (up to 1,500 g/yr) are in line with these Swedish EPA goals, considering that the high end of the ranges in Table 3-7 represent undesirable scenarios.

- The quantity of mercury vapor estimated to be released from monofill disposal (up to 1 kg/yr) is insignificant as compared to other sources such as coal combustion (about 43 tons per year).

Table 3-1. Goal, Criteria, and Subcriteria from EPA/SAIC AHP Brainstorming Session, June 17 and 18, 2004

Goal: Minimize Environmental Impacts During Life Cycle

First-Level Criterion (weights as calculated by Expert Choice in parentheses)	**Second-Level Criterion** (weights as calculated by Expert Choice in parentheses)	**Purpose of Criterion**	**Intensities**[a]	**Expert Choice Pairwise Comparison Matrix for Intensities**[c]
C1. --during routine operation of the stabilization facility[b] (0.065)	C1-1. -solid waste streams (other than final product) (0.750)	To assess the amount of solid waste (other than the final product) requiring disposal	low (1.0) moderate (0.65) high (0.265)	Low | Mod. | High Low | | 3 Mod. | High
	C1-2. -atmospheric discharges (0.250)	To assess the level of atmospheric discharges from the facility	low (1.0) moderate (0.55) high (0.303)	2 Low | Mod. | High 3 Low | | 3 Mod. | High
C2. --during abnormal or accidental operation of the stabilization facility (0.188)	C2-1. -elemental mercury spills (0.833)	To assess the potential for environmentally harmful spills of liquid elemental mercury during accident conditions	low (1.0) moderate (0.55) high (0.303)	2 Low | Mod. | High 2 Low | | 3 Mod. | High
	C2-2. -spills other than elemental mercury (0.167)	To assess the potential for environmentally harmful spills of materials other than liquid elemental mercury during accident conditions	low (1.0) moderate (0.55) high (0.303)	2 Low | Mod. | High 2 Low | | 3 Mod. | High | 2
C3. --during transportation (0.216)	C3-1. -of mercury to stabilization facility (0.747)	To assess the potential for accidental spills of elemental mercury during transportation	No (1.0) Yes (0.111)	| 2 | Yes No | Yes
	C3-2. -of stabilized waste to monofill (0.119)	To assess the potential for accidental releases of stabilized waste during transportation to monofill	None (1.0) Encapsulated (0.225) Not encapsulated (0.127)	No | E | NE N | | 7 9 E N NE
	C3-3. --of reagents to stabilization facility (0.134)	To assess the potential for accidental releases of reagents during transportation	low (1.0) moderate (0.405) high (0.164)	5 Low | Mod. | High 2 Low | | 5 Mod. | High 2

3

Table 3-1. Goal, Criteria, and Subcriteria from EPA/SAIC AHP Brainstorming Session, June 17 and 18, 2004 (continued)

<table>
<tr><th>First-Level Criterion
(weights as calculated by Expert Choice in parentheses)</th><th>Second-Level Criterion
(weights as calculated by Expert Choice in parentheses)</th><th>Purpose of Criterion</th><th>Intensities[a]</th><th>Expert Choice Pairwise Comparison Matrix for Intensities</th></tr>
<tr><td>C4. –during decommissioning of the stabilization unit
(0.038)</td><td>None</td><td>To assess the potential for potentially harmful environmental effects during decommissioning</td><td>low (1.0)
moderate (0.55)
high (0.303)</td><td><table><tr><td></td><td>Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td></td><td></td><td>3</td></tr><tr><td>Mod.</td><td></td><td></td><td></td></tr><tr><td>High</td><td></td><td></td><td></td></tr></table></td></tr>
<tr><td rowspan="2">C5. --during storage in the monofill
(0.493)</td><td>C5-1. - expected ease of maintaining environmental conditions (up to 40 years)
(0.200)</td><td>To assess the potential for excessive leaching during storage</td><td>low (1.0)
moderate (0.225)
high (0.127)</td><td><table><tr><td></td><td>2
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td></td><td>2</td><td>7</td></tr><tr><td>Mod.</td><td></td><td></td><td></td></tr><tr><td>High</td><td></td><td></td><td></td></tr></table></td></tr>
<tr><td>C5-2. -expected long-term susceptibility to degradation
(0.800)</td><td>To assess long-term stability</td><td>low (1.0)
moderate (0.225)
high (0.127)</td><td><table><tr><td></td><td>5
Low</td><td>Mod.</td><td>High</td></tr><tr><td>Low</td><td></td><td>2</td><td>7</td></tr><tr><td>Mod.</td><td></td><td></td><td></td></tr><tr><td>High</td><td>5</td><td></td><td></td></tr></table></td></tr>
</table>

a In order of decreasing desirability. Values in parentheses are weightings calculated by the Expert Choice software after the pairwise comparison that is summarized in the adjacent column.

b Includes macroencapsulation where relevant.

c. Shaded areas represent areas of the matrix that are not used by the Expert Choice Software. The numbers in the matrices represent the relative importance of the intensities as determined by pairwise analysis. For example, in the case where there is a 2 in the cell that has “low” to the left and “mod” above, the team judged that it is twice as desirable for a technology to have a low intensity than a moderate intensity. For a more detailed explanation of the Expert Choice matrices, see Appendix A.

Table 3-2. Expert Choice Matrices for Criteria and Subcriteria

Table 3-2a. – First Level Criteria

	C1.[a]	C2.	C3.	C4.	C5.
C1.		-3[b]	-4	2	-7
C2.			1	5	-3
C3.				7	-3
C4.					-9
C5.					

a. The numbering system is explained in Table 1

b. A positive number implies that the criterion in the left hand column is more important than the criterion in the top row. A negative number implies that the criterion in the top row is more important than the criterion in the left hand column.

Table 3-2b. – Second level criteria Associated with Criterion 1

	C1-1.	C1-2.
C1-1.		3
C1-2.		

Table 3-2c. – Second Level Criteria Associated with Criterion 2

	C2-1.	C2-2.
C2-1.		5
C2-2.		

Table 3-2d. – Second level criteria Associated with Criterion 3

	C3-1.	C3-2.	C3-3.
C3-1.		7	5
C3-2.			1
C3-3.			

Table 3-2e. – Second Level Criteria Associated with Criterion 5

	C5-1.	C5-2.
C5-1.		-4
C5-2.		

Table 3-3. Assignment of Intensities to Treatment and Disposal Alternatives[1]

Treatment and Disposal Option	Routine Operations		Accidental Releases		Transportation			Decom-missioning	Monofill Storage	
	Solid Waste Discharges	Atmospheric Discharges	Mercury Spills	Other Spills	Mercury to Treatment	Waste to Monofill	Reagents		< 40 years	> 40 years
Option A+ NME[a] + CTA[c]	Moderate[e]	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Moderate
Option A+ NME[b] + MTA[d]	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Moderate
Option A+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option A+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option B+ NME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Moderate	Low
Option B+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Low	Low	Moderate	Low
Option B+ ME + CTA	Moderate	Low	Moderate	Low	Yes	No	Low	Low	Low	Low
Option B+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Low	Low	Low	Low
Option C+ NME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ NME + MTA	Moderate	Low	Moderate	Low	No	NME	Moderate	Low	Low	Moderate
Option C+ ME + CTA	Low	Low	Moderate	Low	Yes	No	Moderate	Low	Low	Moderate
Option C+ ME + MTA	Moderate	Low	Moderate	Low	No	ME	Moderate	Low	Low	Moderate

1. The assignment of these intensities is discussed in Appendix B. The uncertainty analysis (Section 3.7.2) helps to quantify the impacts of these selections.
a. NME = Not Macroencapsulated. b. ME = Macroencapsulated.
c. CTA = Centralized Treatment Alternative. d. MTA = Mobile Treatment Alternative.

Table 3-4. Environmental Analysis - Summary of Baseline Results for 12 Evaluated Alternatives

Treatment Scenario			Overall Ranking	
Treatment Process	Macro-Encapsulation	Fixed or Mobile Facility	Score (as fraction of 1,000)	Rank (Best to Worst)
Option A	With	Mobile	117	1
Option B	With	Mobile	117	1
Option B	Without	Mobile	108	3
Option A	With	Fixed	98	4
Option B	With	Fixed	98	4
Option B	Without	Fixed	89	6
Option C	Without	Mobile	73	7
Option C	With	Mobile	73	7
Option A	Without	Mobile	66	9
Option C	Without	Fixed	57	10
Option C	With	Fixed	57	10
Option A	Without	Fixed	48	12
Number of alternatives evaluated			12	—
Total			1,000	—
Average score (total divided by 12, the number of alternatives)			83	—

Shading indicates the highest-ranking alternatives.
Distributive mode; overall inconsistency factor from Expert Choice: 0.02 (good).
Average value is provided for reference and identifies the average score for the twelve evaluated technologies.

Table 3-5. Environmental Sensitivity Analysis

Treatment Scenario			Ranking[a]													
			Baseline (from Table 3-4)		Importance on Disposal				Importance on Transport				Importance on Accidents			
Treatment Process	Macro-Encapsulation	Fixed or Mobile Facility			Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low		Sensitivity: High		Sensitivity: Low	
			Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Option A	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	With	Mobile	117	1	124	1	110	1	120	1	115	1	108	1	120	1
Option B	Without	Mobile	108	3	111	5	105	3	113	3	105	5	101	3	110	3
Option A	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	With	Fixed	98	4	115	3	82	7	85	4	106	3	94	4	100	4
Option B	Without	Fixed	89	6	102	6	78	9	79	9	96	6	88	6	90	6
Option C	Without	Mobile	73	7	60	7	85	5	84	7	66	7	76	7	72	7
Option C	With	Mobile	73	7	60	7	86	4	85	4	66	7	76	7	72	7
Option A	Without	Mobile	66	9	48	11	84	6	81	8	57	11	71	9	64	9
Option C	Without	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option C	With	Fixed	57	10	52	9	61	10	52	10	60	9	64	10	54	10
Option A	Without	Fixed	48	12	39	12	56	12	47	12	48	12	57	12	44	12
Average			83	—	83	—	83	—	83	—	83	—	83	—	83	—
Total			1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—	1,000	—

Shading indicates the highest-ranking alternatives. In the sensitivity analysis for each criterion, the importance of the criterion is set at higher or lower than its baseline value, as identified in the text. The four other criteria comprise the remainder, proportional to their original contributions.

a. Scores normalized to total 1,000.

Table 3-6. Uncertainty Analysis for Mercury Management Alternatives

Ref. No.	Alternative			Criteria	Change in Intensity for Uncertainty Analysis		Initial Result (Table 3-4)		Uncertainty Analysis Result	
					Baseline	Change	Score	Rank	Score	Rank
0	All			Baseline for comparison: Same results as Table 3-4			—	—	—	—
1	**Treatment Process**	**Macro-Encapsulation**	**Fixed or Mobile Facility**	Monofill Disposal, >40 years	Moderate	Low				
	Option C	Without	Mobile				73	7	99	3
	Option C	With	Mobile				73	8	99	3
	Option C	Without	Fixed				57	10	82	6
	Option C	With	Fixed				57	11	82	6
2	Option A	Without	Fixed	Monofill Disposal, <40 years	Moderate	Low	48	12	55	12
3				Monofill Disposal, >40 years	Moderate	Low			84	6
4				Monofill Disposal, both <40 years and >40 years	Moderate	Low			92	4
5	Option B	With	Mobile	Monofill Disposal, <40 years	Low	Moderate	117	2	108	2
6				Monofill Disposal, >40 years	Low	Moderate			76	6
7				Monofill Disposal, both <40 years and >40 years	Low	Moderate			68	9
8	Option B	Without	Mobile	Accidental Releases (Mercury Spills)	Moderate	Low	108	3	117	1
9						High			102	3
10	Option C	With	Fixed		Moderate	Low	57	11	66	9
11						High			51	11

Table 3-7. Preliminary Release Rates for Mercury Monofill Disposal

Pathway	Mercury Quantity, MT	Hg Concentration	Design Basis	Monofill size, acre	Release, g/yr
Leachate	5,000 MT	0.01 – 1 mg/L	5% Infiltration Rate; Precipitation of 5 –60 in/yr (continental U.S. range)	0.6 – 1	0.2 – 300
	12,000 MT			1.3 – 2.2	0.3 – 700
	25,000 MT			3 – 5	0.8 – 1,500
Volatilization	1,000 MT/yr	0.01 – 10 mg/m3	Maximum gas generation 100 m3/MT (AP-42)	---	1 – 1,000

4.0 ECONOMIC ANALYSIS

The purpose of this chapter is to provide estimates of the cost of various methods for the long-term disposition of elemental mercury. As previously described, twelve treatment alternatives are under consideration:

1. Option A + no macroencapsulation + centralized treatment
2. Option A + no macroencapsulation + mobile treatment
3. Option A + macroencapsulation + centralized treatment
4. Option A + macroencapsulation + mobile treatment
5. Option B + no macroencapsulation + centralized treatment
6. Option B + no macroencapsulation + mobile treatment
7. Option B + macroencapsulation + centralized treatment
8. Option B + macroencapsulation + mobile treatment
9. Option C + no macroencapsulation + centralized treatment
10. Option C + no macroencapsulation + mobile treatment
11. Option C + macroencapsulation + centralized treatment
12. Option C + macroencapsulation + mobile treatment

Three different masses of mercury were considered for each of the treatment alternatives:

a. 5,000 metric tons,
b. 12,000 metric tons, and
c. 25,000 metric tons.

Thus, 36 treatment and disposal alternatives were considered. In addition, cost estimates have been prepared for long-term storage of the three masses of elemental mercury in aboveground facilities without any treatment or disposal efforts, making a total of 39 cost estimates in all. This chapter presents the approach, the cost estimate results, and the assumptions used in producing the cost estimates.

Each of the thirty-six cost estimates for treatment and disposal includes the following elements:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative)
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternative,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contain the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space as necessary, and transporting elemental mercury to the storage facility(ies).

In this chapter, Sections 4.1, 4.2, 4.3, and 4.4 describe the assumptions and bases for the cost estimates of the treatment and encapsulation processes, the monofill, storage, and transportation respectively. Section 4.5 discusses uncertainties, and Section 4.6 presents results and interpretation. Various appendices contain detail on input to the cost estimates: Appendix C – Option A Treatment Process; Appendix D – Option B Treatment Process; Appendix E – – Monofill Estimate for Option A Treatment Process; Appendix F – Monofill Estimate for Option B Treatment Process; and Appendix G - Monofill Estimate for Option C Treatment Process. Note that there is no Appendix for the Option C Treatment Process. This is because the Option C vendors provided a great deal of proprietary material. However, the Option C costs were calculated on the same basis as were the costs for the other options.

4.1 Assumptions and Bases for Cost Estimates

This section describes the assumptions and bases for the cost estimates: 4.1.1 General Assumptions; 4.1.2 Mercury Treatment Processes; 4.1.3 Macroencapsulation; 4.1.4 Mobile Treatment alternative; 4.1.5 Monofill; 4.1.6 Storage; and 4.1.7 Transportation.

4.1.1 Background and General Assumptions

- Possibly the most important general assumption is that mercury will be treated at a rate of 1,000 Metric Tons (MT) per year. This is a reasonable assumption in light of the rate at which surplus elemental mercury is becoming available, as is described below.
- For treatment and disposal alternatives, it is assumed that the treatment facility will continue in operation until all of the mercury has been treated and placed in a monofill. This will take 5 years for 5,000 MT, 12 years for 12,000 MT and 25 years for 25,000 MT. Once all of the mercury has been treated, the monofill will be finally closed and monitored for 30 further years.
- For continuing storage alternatives, it is assumed that costs will be calculated for the same length of time as for the corresponding treatment alternative: 5 +30 years for 5,000 MT; 12 + 30 years for 12, 000 MT; and 25 + 30 years for 25,000 MT.
- Costs for each scenario are presented as a Net Present Value (NPV) of a future stream of 2004 constant dollar costs using a 30-year real discount rate of 3.5% per year provided by the Office of Management and Budget (OMB 2004a, 2004b).

According to the Mercury Management Environmental Impact Statement (MMEIS; DLA 2004), the principal amounts of elemental mercury currently in storage at Federal sites in the US are kept in 76 lb (34 kg) flasks at four sites: (a) the New Haven Depot near New Haven, IN; (b) the Somerville Depot in Hillsborough, NJ; (c) the Warren Depot near Warren, OH; and (d) in a building at the U.S. Department of Energy’s Y-12 National Security Complex in Oak Ridge, TN.

At New Haven, Somerville, and Warren, the flasks are stored in 30-gal (114-1) steel drums for extra protection, called “overpacking.” Each drum contains 6 flasks. The overpack drums meet the U.S. Department of Transportation’s (DOT’s) packaging requirements for shipping hazardous materials by highway or rail (*Title 49 Code of Federal Regulations* [CFR] 173.164(d)(2)). The drums are banded together in groups of 5 and stored on metal catch trays. The catch trays are on 4-ft (1.2m) square wooden pallets. Each drum contains 456 lb (207 kg) of elemental mercury, and each pallet carries 2,280 lb (2.28 tons or ~ 1 metric ton (MT)).

Many of the flasks at New Haven, Somerville, and Warren are of the older, welded variety made in the 1940s and 1950s. At Y-12, however, the mercury was transferred to newer, seamless flasks in the mid-1970s. These flasks are much less susceptible to leakage and have not been overpacked. They are stored in groups of 45 on wooden pallets that measure 38 in by 38 in by 20 in (96 cm by 96 cm by 51 cm). Thus, each pallet carries 3,420 lb (1,554 kg ~ 1.5 MT) of elemental mercury[17]. The amount of mercury at each site is summarized in Table 4-1.

Table 4-1. Current U.S. Government Mercury Stockpiles[a]

Location	Owner	Quantity in Storage tons/(MT)	Number of Flasks	Number of Drums
New Haven Depot	DNSC	614 (557)	16,151	2,692
Somerville Depot	DNSC	2,885 (2,617)	75,880	12,647
Warren Depot	DNSC	621 (563)	16,355	2,726
Y-12, Oak Ridge	DNSC	770 (699)	20,276[b]	3,379[c]
	DOE	1,130 (1,026)	29,724[b]	4,954[c]
Total	DNSC	4,890 (4,436)	128,662	21,444
	DOE	1,130 (1,026)	29,724	4,954[c]
	All	**6,020 (5,462)**	**158,386**	**26,398**

a. Source: DLA (2004).
b. These stockpiles are collocated in Y-12.
c. Number of drums required to overpack the flasks (currently not overpacked).

Alternative 1 – 5,000 MT

For the case of continued storage, Alternative 1 is quite close to the status quo at DNSC and DOE locations. Therefore, Alternative 1 is costed as if storage will continue there and can be scaled directly from Appendix D of the MMEIS. For example, the current DNSC stockpile of 4,436 metric tons requires approximately 200,000 ft^2 (18,581 m^2) of forklift-accessible flat space inside a structure. 5,000 MT would therefore require ~ 225,000 ft^2 (~ 21,000 m^2), an increase of a factor of 1.127, and items such as rent can be scaled accordingly.

The need for storage will not vanish immediately even if the waste is treated. For the centralized treatment alternative, it is assumed that elemental mercury will be transported from the current storage locations to the treatment facility at a rate of 1,000MT per year for five years. Each 1,000 MT occupies 45,000 ft^2 (~ 4,200 m^2). The MMEIS gives information that can be translated into a cost per MT per year for storing elemental mercury. As the stockpile is depleted, the analysis simplifies by assuming that the storage costs throughout the year are those for the amount of mercury in storage at the mid-point of the year, and that storage costs will decrease accordingly until all the mercury has been treated. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Alternative 2 – 12,000 MT

For this alternative, it is assumed, as for alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 7,000 MT becomes available at a uniform rate over a period of 12 years, i.e., at a rate of 583 MT/yr[18]. For the case of continued storage, therefore, the amount in the stockpile will increase by this amount each year, and additional storage space needs to be made available. As explained above, the amount of mercury in storage at the mid-point of each year is multiplied by the unit yearly cost per MT to provide an estimate of total storage costs per year.

When the waste is treated at a centralized facility, it is assumed that the 583 MT/yr of “new” elemental mercury is transported directly to the treatment facility, thus obviating the need for intermediate

[17] In the cases where this mercury is transported to a central treatment facility, it is assumed that they will first be placed 6 at a time in 30-gal steel drums in order to satisfy DOT requirements.
[18] Note that the assumption that there is about 5,000 MT in existing storage and that additional elemental mercury becomes available at a rate of a few hundred MT per year is consistent with data in Appendix D of the MMEIS.

storage. The remaining 417 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Every year, therefore, there is need for 18,800 ft^2 (1,747 m^2) less storage space. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Alternative 3 – 25,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 20,000 MT becomes available at a uniform rate over a period of 25 years, i.e., at a rate of 800 MT/yr. For the case of continued storage, therefore, the amount in the stockpile will increase by this amount each year, and additional storage space needs to be made available.

When the waste is treated at a centralized facility, it is assumed that the 800 MT/yr is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining 200 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. The same rate of depletion of the existing stockpile is assumed for both the centralized and mobile treatment alternatives.

Observation

Note that the authors of Appendix D of the MMEIS calculated that approximately 388 MT of elemental mercury was added to inventory in 1997. As noted above, the 12,000 MT and 25,000 MT alternatives assume that elemental mercury becomes available at the rate of 583 MT/yr and 800 MT per year, respectively. These rates are within a factor of about two of the 1997 experience. The current work did not include an analysis of whether there is enough mercury in consumer inventories in the US and a sufficient rate of decommissioning to ensure that total amounts of 12,000MT or 25,000 MT will in fact be made available for long-term disposal. However, the assumed rate of disposal of 1,000 MT per year is not unreasonable.

4.1.2 Mercury Treatment Processes

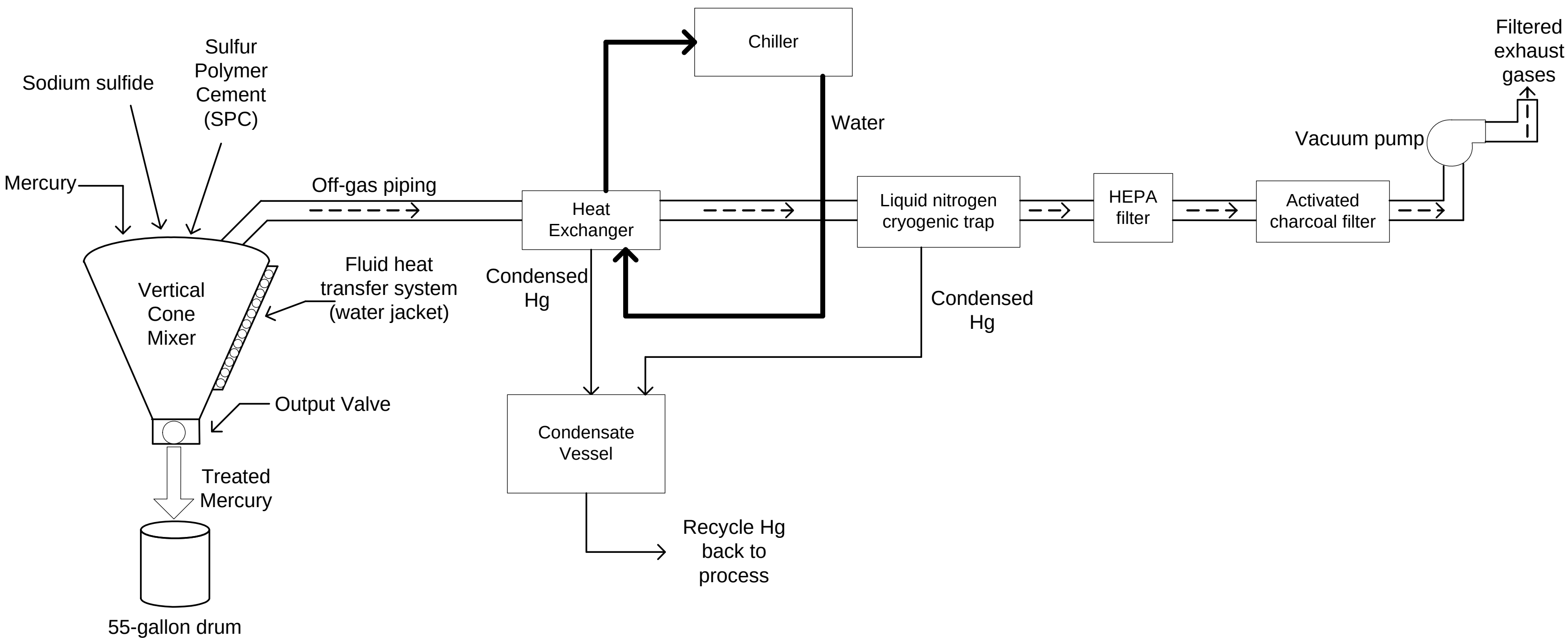
This section provides assumptions and bases for the costs of each of the three treatment technologies.

4.1.2.1 Option A

Option A is a process developed to treat elemental mercury and mercury contaminated waste and debris. Option A is a two stage, single vessel batch process that results in mercuric sulfide stabilized in a sulfur polymer matrix. In the process' first step, mercury is reacted with powdered sulfur polymer cement and additives to form a stable mercury sulfide compound. Next, the chemically stabilized mixture is melted, mixed, and cooled to form a monolithic solid waste form in which the stabilized mercury particles are microencapsulated within a sulfur polymer matrix.

A process diagram is shown in Figure 4-1. The process's two main steps, (1) reaction of mercury with sulfur and (2) melting/mixing in a sulfur polymer matrix, occur in a vertical mixer/dryer. The process requires some heating, so the mixer is jacketed for heat transfer. The process produces some mercury vapor, so a ventilation system is required to filter out the vapor. Since the process is heated, heat exchangers are included in the ventilation system.

Figure 4-1. Option A Process



Appendix C includes further diagrams for the Option A process that show the equipment and materials used for the cost estimates. Each of the diagrams shows the sizing for process capacity, reagent consumption, and the major equipment. The assumptions shown on the process diagram are described below.

The following is the key information for sizing the Option A process: one 35 ft^3 mixer can process 525 kg per shift. This mixer size was based on published information in which the vendor states that a 35 ft^3 mixer is under development. This represents a scaling up by a factor of 35 from the pilot mixer of 1 ft^3. Five mixers in parallel operating two shifts per day can process the assumed mass of mercury per year (1,000 metric tons). The major equipment necessary to operate these mixers is shown on the process diagram, which lists the major equipment and its cost. These costs are summarized in Table 4-2. The cost of the major equipment is used to estimate the overall capital costs for the Option A process.

Table 4-2. Major Equipment for the Option A Process

Component	Price	Reference	Comments
Sulfur Polymer Cement Feeders	$44,100	RES (2002) account 100-55, page 2	Conveyer 20-525 cf/hr
Sulfur Polymer Cement Hopper	$10,650	Perry and Green (1997) Table 9-50	$\$4{,}700 \cdot \left(\frac{4{,}200}{1{,}000}\right)^{0.57}$ $= \$10{,}650$
Sodium Sulfide Pump	$15,000	Bubb (2004a)	Vertical Pump and electric motor. Designed for concentrated acid.
Sodium Sulfide Feed Valves	$330	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, 200#, Socket Weld, ¾ -inch Sch 40.
Sodium Sulfide Tank	$557	MSC (2004)	Polyethylene Double-Walled Tank 100 gal
Mixer	$180,000	Bubb (2004b)	Vertical Vacuum Blender 35 cubic feet Jacketed Motor, Valves, Controls, Thermocouples
Heater	$26,495	Bubb (2004b)	72 kW
Liquid Nitrogen Tank	$627	LACO (2004)	2L N2 reservoir (16 hour holding time)
Off-gas Ducts	$506.47 per 100 ft^2 = $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20” diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004) pg 3575	Air Handler HEPA Air Filter 1,100 CFM, 24”x24”x11.5”, 99.97% efficient
Carbon Filter	$47.25	Grainger (2004) pg 3571	Activated Carbon Disposable Filters 250 FPM, 24”x24”x2”
Vacuum Pump	Pump $4,800 Electric Motor $1,187 Total: $5,987	RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Assumed similar cost to a fan: Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Chiller	$5,366	MSC (2004) page 4477	Lytron RC045 20,100 BTU/hr, 4.3 gpm Pump
Condenser	$4,186	MSC (2004) page 4476	Liquid-to-air heat exchanger model 6640 x 2 + $2,000 allotment for vessel and manufacturing
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Notes: price gives the costs for one piece of equipment. Quantities of equipment required are given in Appendix C.

The key information for the mass components in each treatment batch is as follows:

- 33% weight mercury,
- 65% weight sulfur polymer cement, and
- 2% weight sodium sulfide.
-

Thus, the mass of treated product is approximately 3 kg/kg mercury treated.

For 1,000 MT of mercury processed per year, this sets the amount of reagents required per year. This also means that there are 3,000 MT of waste product for disposal each year. Table 4-3 lists the materials used in the Option A process and their costs. This includes reagents and drums into which treated mercury is placed.

Table 4-3. Material Costs for Option A Process

Component	Price	Reference	Comments
Sulfur Polymer Cement	$0.12 / lb delivered ($0.264/ kg)	Chang (2001)	Martin Resources (Odessa, TX) Chement 2000
Sodium Sulfide	$10.53 / kg delivered	Lab Depot (2004)	Na_2S (36% water of crystallization) 1.5 g/cm^3
55-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	

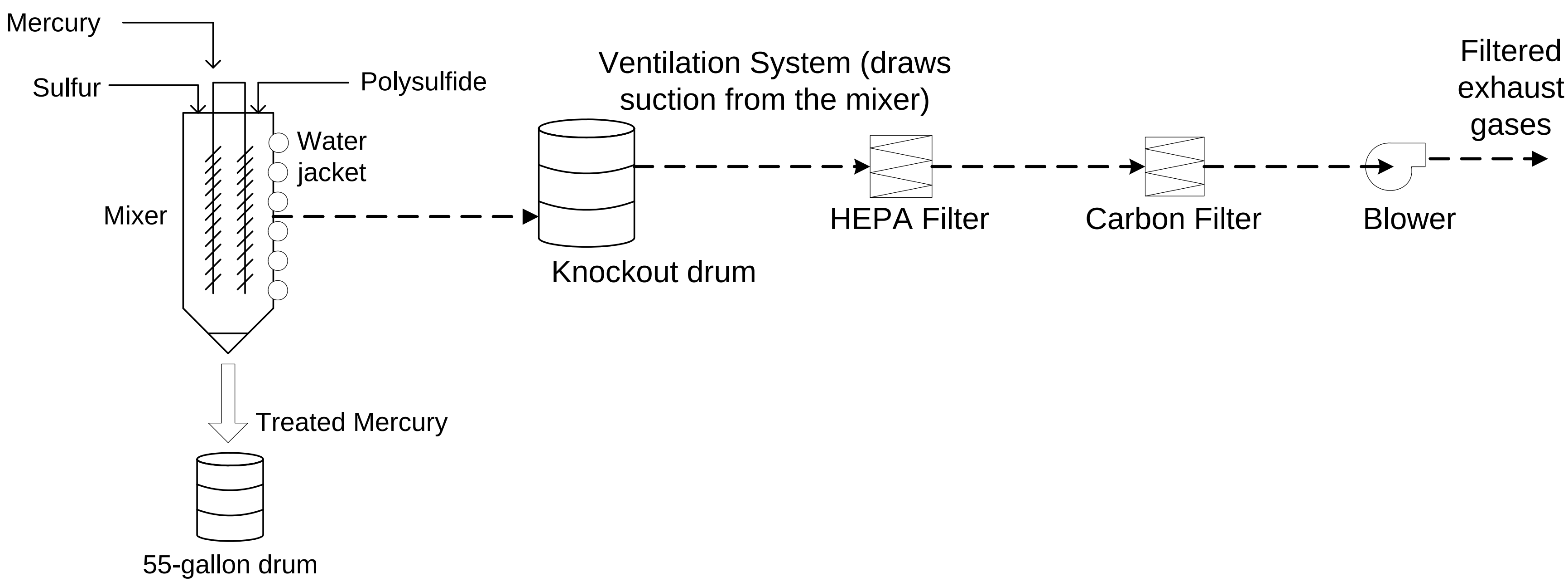
Staff salary costs and utility costs for the Option A treatment process are estimated on the process diagram in Appendix C. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on the Website Salary.com (Salary.com 2004). For all three options, the calculated O&M costs include the assumption that the facility is down 20% of the time for maintenance and repair.

4.1.2.2 Option B

The Option B process treats elemental mercury or mercury containing wastes. A process diagram is shown in Figure 4-2. The process, performed in batches, consists of the following steps:

1. A sulfur-containing compound (otherwise known as the amalgamating agent), preferably elemental sulfur in powdered form, is spread throughout a mixer.
2. The mercury-containing material is added to the mixer and mixed.
3. A polysulfide is added and mixed to activate the reaction between sulfur and mercury. Typically this polysulfide is calcium polysulfide or sodium polysulfide.
4. The resulting granular waste is poured into drums.

Figure 4-2. Option B Sulfide Process



As with the Option A process, a ventilation system with filters is required. Appendix D includes further diagrams for the mercury treatment processes that show the equipment and materials used for the cost estimates. Each of the diagrams shows the sizing for process capacity, reagent consumption, and the major equipment. The assumptions and sources of information shown on the process diagrams are discussed below.

The following is the key information for sizing the Option B process:

- 375 kg of mercury per batch[19],
- 3 batches per mixer-shift, and
- 80% utilization of the equipment.

Using this information, five mixers operating in parallel can process the required mass of mercury per year (1,000 tons). The major equipment necessary to operate these mixers is shown on the process diagram, and Table 4-4 lists the major equipment and its cost. The cost of the major equipment is used to estimate the overall capital costs for the Option B process.

The following is the key information regarding the mass components in each treatment batch:

- 67% mercury,

3% polysulfide, and30% sulfur.Thus, the mass of treated product is approximately 1.5kg/kg mercury treated.

For 1,000 tons of mercury processed per year, this sets the amount of reagents required per year. This means that 1,500 MT of waste product needs to be disposed of each year from the Option B process. Table 4-5 lists the materials used in the process and their costs. This includes reagents and drums into which treated mercury is placed.

Staff salary costs and utility costs for the treatment process are estimated on the process diagram. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on information from Salary.com.

4.1.2.3 Option C

The final product of Option C is a monolithic amalgamated material that is encapsulated in polyethylene-lined steel drums. The process, which is performed in batches in drums, consists of steps to create an amalgam and (if required) additional steps to create a stabilized form. A process diagram is shown in Figure 4-3.

The process steps are as follows:

1. A proprietary powdered reagent is added to elemental mercury in a drum and mixed.
2. Another proprietary powdered reagent is added to the drum and mixed.
3. A proprietary liquid reagent is added to the drum and mixed.
4. The stabilized form is created by mixing in three more proprietary reagents (two powdered, one liquid) and curing.

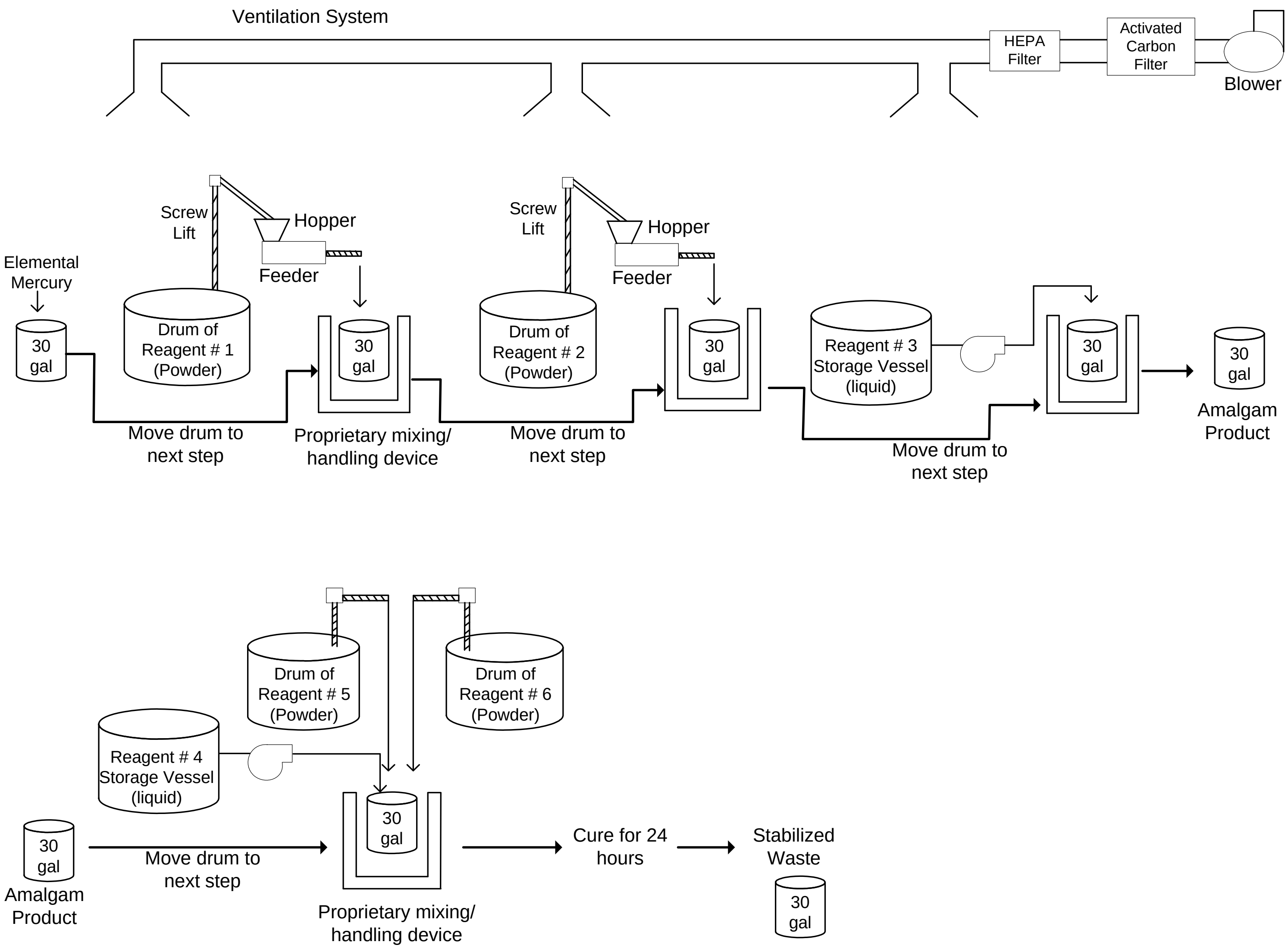
[19] This batch size was confirmed in discussions with Vendor B and represents scaling up by a factor of five from the existing mixer.

Table 4-4. Major Equipment for the Option B Process

Component	Price	Reference	Comments
Mixers	$65,000	Bubb (2004d)	60 cubic foot mixer
Polysulfide Pumps	Pump $2,400 Electric Motor $1,187 Total= 3,587	RES (2002) account 100-280, page 2 RES (2002) account 100-653, page 2	Pump Vertical Split Case Centrifugal Pump Max operating pressure 285 psi 50 gpm and 200 ft of head 7.5 HP Electric Motor 7.5 HP AC Motor
Polysulfide Feed Valves	$760	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, Screwed 2-inch Sch 40
Sulfur Hoppers	$26,400	RES (2002) account 100-45, page 4	Gravimetric Feeder 720 – 24,000 lb / hr
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Water Heater	$2,769	RES (2002) account 15-28, page 2	Commercial water heater, gas 50 gallons, 90,000 BTU/hr
Ventilation System Ducts	$506.47 per 100 ft^2 = $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20" diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004)	Air Handler HEPA Air Filter 1,100 CFM, 24"x24"x11.5", 99.97% efficient
Carbon Filter	$47.25	Grainger (2004)	Activated Carbon Disposable Filters 250 FPM, 24"x24"x2"
Knockout Drum	$6,300	Perry and Green (1997) page 9-69	Pressure Vessel Horizontal Drum 1,000 gal
Blower	Fan $4,800 Electric Motor $1,187 Total: $5,987	Fan RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Fan Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Notes: price gives the costs for one piece of equipment. Quantities of equipment required are given in Appendix D.

Figure 4-3. Option C Process



As with the other processes, a ventilation system with filters is required.

No Appendix is shown for this process to protect proprietary details. The principal assumptions and sources of information for costing the process are described below.

Two parallel amalgamation process lines and three parallel stabilization process lines can treat 1000 tons of mercury per year. The processes will operate two shifts per day. The major equipment necessary to operate these process lines is shown on the process diagram in Attachment C, and Table 4-6 lists the major equipment and its cost. The cost of the major equipment is used to estimate the overall capital costs for the Option C process.

Table 4-5. Material Costs for Option B Process

Component	Price	Reference	Comments
Polysulfide	$0.31 / lb delivered ($0.682 / kg)	Gragg (2004)	LA Chemical
Sulfur	$0.17 / lb delivered ($0.374 / kg)	Bubb (2004e)	Georgia Gulf Sulfur
55-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	

The costs and the chemical forms of the reagents in the Option C Process constitute proprietary information. Table 4-7 lists the materials used in the process and their costs. Note that the drums in which mercury is treated are 22 gallons for this cost estimate. The drum size was reduced so that the treated mercury filled 90% of the container volume, meeting the monofill requirement. The mass of waste product is 5.66 kg/kg of treated Hg.

Staff salary costs and utility costs for the treatment process are estimated on the process diagram. These costs are included in the annual O&M costs for the treatment process. Staff salary is based on information from Salary.com, and the number and type of staff required were provided by the vendor.

4.1.2.4 Cost Input Factors Common to All Treatment Technologies

Total capital costs are estimated as a percentage of the costs for the major equipment; that is, elements of the total capital cost are calculated by multiplying factors that are applied total major equipment costs. The factors used are shown in Table 4-8. The bases for the factors are given in the notes under the table.

4.1.2.5 Operating and Maintenance Costs

Direct operating costs for treatment (and macroencapsulation) are estimated on the Process Diagram sheets included in Attachments C and D (for Options A and B). The costs for Option C were calculated in the same way. Flask disposal costs ($0.44 per kilogram of mercury processed) included in the treatment O&M are based on Bethlehem (2001). Costs, overhead, fees, and contingency are based on factors that are shown in Table 4-9. The bases for the factors are given in the notes under the table.

Table 4-6. Major Equipment for the Option C Process

Component	Price	Reference	Comments
Drum Mixer	$1,404	MSC (2004) pg. 4481	TEXP Mixer 1.5 HP
Drum Truck	$321	MSC (2004) pg. 3196	Steel Deck Platform Truck 2,500 lb 30”x60”x40”
Mixing and Handling Device	$3,725	NA	Use the Mixer and Truck items above plus a $2,000 allowance for customization of the assembly (e.g. frame, brakes, track).
Lift/Hopper/Feeder	$8,385	Flexicon (2004)	Flexicon Stainless Steel, 50 cubic ft / hr 10 ft long, 4.5” OD
Reagent 3 and 4 Pumps	Pump $2,400 Electric Motor $1,187 Total: $3,587	RES (2002) account 100-280, page 2 RES (2002) account 100-653, page 2	Pump Vertical Split Case Centrifugal Pump Max operating pressure 285 psi 50 gpm and 200 ft of head, 7.5 HP Electric Motor 7.5 HP AC Motor
Reagent 3 and 4 Feed Valves	$760	RES (2002) account 15-47, page 27	Stainless Steel Gate Valves, Screwed 2-inch Sch 40
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Ventilation System Ducts	$506.47 per 100 ft^2. Total= $5,065	RES (2002) account 15-9, page 1	24 GA ductwork (20” diameter), 1000 ft^2
HEPA Filter	$306.50	Grainger (2004)	Air Handler HEPA Air Filter 1,100 CFM, 24”x24”x11.5”, 99.97% efficient
Carbon Filter	$47.25	Grainger (2004)	Activated Carbon Disposable Filters 250 FPM, 24”x24”x2”
Blower	Fan $4,800 Electric Motor $1,187 Total: $5,987	Fan RES (2002) account 100-110, page 2 RES (2002) account 100-653, page 2	Fan Vaneaxial Fan 44-inch diameter 1 – 30 HP 15,000 – 47,000 CFM Electric Motor 7.5 HP AC Motor
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Note: price gives the costs for one piece of equipment.

Table 4-7. Material Costs for the Option C Process

Component	Price	Reference	Comments
Reagents	Proprietary		
22-gallon drums	$33 per barrel delivered	Ten Siethoff (2004c)	Assume, since not a standard barrel size, that the barrels will cost the same as 55-gallon barrels.

Table 4-8. Factors Used to Estimate Fixed Treatment Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Building site preparation	0.08	0.15	0.22	2
Building construction, services installation	0.26	0.305	0.35	2
Cost to install major equipment	0.39	0.41	0.43	2
Piping	0.30	0.345	0.39	2
Structural foundations (steel, concrete)	0.28	0.28	0.28	3
Electrical	0.08	0.125	0.17	2
Instruments	0.13	0.13	0.13	2
Auxiliaries	0.48	0.515	0.55	2
Other field expenses	0.35	0.39	0.43	2
Engineering	0.35	0.39	0.43	2
Initial start-up costs	0.02	0.13	0.24	4
Fees, overhead, and profit	0.09	0.13	0.17	2
Contingency	0.39	0.39	0.39	2

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by the factor to make an allowance for equipment not yet identified.
2. From Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. From Table 9-51 of Perry and Green (1997) for fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

Table 4-9. Factors Used to Estimate Treatment and Macroencapsulation O&M Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Maintenance and Repair	0.02	0.06	0.10	1
Insurance	0.01	0.01	0.01	1
Property tax	0.02	0.02	0.02	1
Other overhead	0.055	0.055	0.055	2
Fee	0.20	0.20	0.20	3
Contingency	0.39	0.39	0.39	4

Notes:

1. Percentage of the major equipment costs (including the allowance for equipment not yet identified) for the treatment or macroencapsulation facility based on guidance in Perry and Green (1997).
2. Percentage of the direct plus indirect costs based on guidance in Perry and Green (1997).
3. Percentage of the direct plus indirect costs based on vendor information for similar process.
4. Percentage of the direct plus indirect costs based on guidance in Perry and Green (1997) for capital costs.

4.1.3 Macroencapsulation

ARROW-PAK macroencapsulation is a process offered by Boh Environmental that places waste into steel drums that are then sealed inside HDPE pipe (DOE 2002; USEPA 2002d). As part of the three treatment processes considered here, the waste is placed in drums. The macroencapsulation process adds the following steps:

1. The drums are placed into ARROW-PAK tubes (HDPE pipe) using a forklift fitted with a plunger and a purpose-built loading rack.
2. The ARROW-PAK tubes are sealed at both ends with HDPE endcaps that are fused to the pipe.

Attachments C and D (for Options A and B respectively) each include a diagram for the macroencapsulation process that shows the equipment and materials used for the macroencapsulation cost estimates . The macroencapsulation costs for Option C were calculated similarly. While the major equipment used for the macroencapsulation process is the same for every mercury treatment process, the material quantities vary with the amount of waste produced by each process. This section describes the assumptions and sources of information shown on the macroencapsulation process diagram.

Table 4-10 lists the major equipment and costs for the macroencapsulation process. The cost of the major equipment is used to estimate the overall capital costs for the macroencapsulation process. The materials' costs for macroencapsulation are listed in Table 4-11.

Table 4-10. Major Equipment for Macroencapsulation

Component	Price	Reference	Comments
Crane	$78,000	RES (2002) account 100-495, page 4	Overhead traveling bridge crane, Floor operated 3 ton, 75 foot span
Waste loading rack	$2,400	Global Industrial (2004)	Increased costs of commercial pallet racks to account for customization required for this application.
Fusion equipment	$3,500	MSC (2004) pg 962	Assume capital required is similar to arc welding machine
Chocks	$43	Grainger (2004) pg 2346	
Forklift	$25,000	Solis (2004)	4,000-6,000 lb capacity Electric Drive

Note: price gives the costs for one piece of equipment.

Table 4-11. Material Costs for Macroencapsulation Process

Component	Price	Reference	Comments
Arrow-Pak tubes	$45/foot	Bubb (2004f)	Estimated as HDPE pipe
Arrow-Pak endcaps	$250 per endcap	Ten Siethoff (2004d)	Estimated as HDPE endcaps

As with the treatment facility capital costs, total capital costs are estimated as a percentage of the costs for the major equipment. The factors used for a macroencapsulation facility at a fixed site are shown in Table 4-12. The bases for the factors are given in the notes under the table.

Staff salary costs and utility costs for the macroencapsulation process in Options A and B are estimated on the process diagrams in Appendices C and D. These costs are included in the annual O&M costs for macroencapsulation. The costs for Option C are calculated similarly. Staff salary is based on information from Salary.com.

4.1.4 Mobile Treatment

The size of the treatment facilities for the centralized alternative is such that it is perfectly feasible to skid mount them and transport them from site to site. The base case alternative is one in which there is a single mobile facility capable of treating 1,000 MT per year that is moved from site to site as needed. Potential alternatives are ones with somewhat smaller capability (say 500 MT/year or 330 MT/year) so that mercury can be treated at more than one site at once.

Facility relocation costs are estimated as the sum of the following: transportation of equipment, assembling the treatment facility, start-up, and contingency. The sum is the cost for one move. Total costs over the span of processing will depend on the number of facility relocations that occur.

Table 4-12. Factors Used to Estimate Fixed Macroencapsulation Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Building site preparation	0.08	0.15	0.22	2
Building construction, services installation	0.26	0.305	0.35	2
Cost to install major equipment	0.19	0.21	0.23	3
Other field expenses	0.10	0.11	0.12	3
Engineering	0.35	0.39	0.43	4
Initial start-up costs	0.02	0.13	0.24	5
Fees, overhead, and profit	0.30	0.315	0.33	3
Contingency	0.26	0.26	0.26	3

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by this factor to make an allowance for equipment not yet identified.
2. Considered as additional space that would be added to the building used for treatment. Factor is from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. Used factors from Table 9-51 of Perry and Green (1997) for solids processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Used factors from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
5. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

As with the fixed facility capital costs, total capital costs for mobile treatment are estimated as a percentage of the costs for the major equipment. The Factors used are shown in Table 4-13. The bases for the Factors are given in the notes under the table. The category for Other Field Expenses, which was included in capital costs for the fixed facility, has been deleted since those costs are associated with construction of a fixed facility. Costs for transportation of equipment between locations for mercury treatment have not been estimated. They are assumed to be contained within the uncertainty bands on the O&M cost estimates (see Section 4.2).

Assembling the treatment process lines is estimated to cost 1/3 as much as installing equipment in a fixed facility. The cost to install equipment in a fixed facility is based on a percentage of the major equipment costs. Costs for macroencapsulation facility assembly following moves are assumed to be negligible.

Start-up of the facility is estimated to cost 1/10 as much as the initial start-up costs for the mobile facility, which are given as part of the capital costs.

Contingency is estimated as a percentage of the rest of the facility relocation costs (the factor is 0.39) based on guidance in Perry and Green (1997) for capital costs.

Table 4-13. Factors Used to Estimate Mobile Treatment Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Steel for skids	0.28	0.28	0.28	2
Cost to assemble major equipment skids	0.26	0.273	0.287	3
Piping	0.30	0.345	0.39	4
Electrical	0.08	0.125	0.17	4
Instruments	0.13	0.13	0.13	4
Auxiliaries	0.48	0.515	0.55	4
Engineering	0.70	0.78	0.86	5
Initial start-up costs	0.02	0.13	0.24	6
Fees, overhead, and profit	0.09	0.13	0.17	4
Contingency	0.39	0.39	0.39	4

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by the factor to make an allowance for equipment not yet identified.
2. From Table 9-51 of Perry and Green (1997). Used the factor for structural steel foundations for fluid processing plant. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. 2/3 of the factor used for installation of equipment for a fixed solids-fluid facility. Assembly of plant following relocations is accounted for in Facility Relocation table. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. From Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values.
5. Double the factor used for engineering for a fixed facility. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
6. Initial start-up costs are taken from Equation 9-260 of Perry and Green (1997). The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

For the mobile treatment alternative, the macroencapsulation module is also mobile. As with the treatment facility capital costs, total capital costs are estimated as a percentage of the costs for the major equipment. The factors used are shown in Table 4-14. The bases for the factors are given in the notes under the table.

4.1.5 Content of Appendices C and D

Appendices C and D contain detailed input to the cost estimates for two of the three treatment technologies: Option A and Option B. There is a similar Appendix for Option C but, since it contains proprietary information, it is not included here. Each Appendix contains:

- Treatment Process Diagrams that also double as worksheets that estimate cost of equipment, costs of reagents, waste volume, staff, etc.
- A table of treatment capital costs for fixed facilities
- A table of treatment capital costs for mobile facilities
- A table of treatment O&M costs
- A table of facility relocation costs
- Macroencapsulation diagrams that also double as worksheets
- A table of macroencapsulation capital costs for fixed facilities
- A table of macroencapsulation capital costs for mobile facilities
- A table of macroencapsulation O&M costs

Table 4-14. Factors Used to Estimate Mobile Macroencapsulation Facility Capital Costs

Cost Element	Factor Used in Cost Estimate			Note
	Minimum	Best	Maximum	
Allowance for equipment not yet identified	0.10	0.15	0.20	1
Cost to assemble major equipment skids	0.127	0.14	0.153	2
Other field expenses	0.10	0.11	0.12	3
Engineering	0.35	0.39	0.43	4
Initial start-up costs	0.02	0.13	0.24	5
Fees, overhead, and profit	0.30	0.315	0.33	3
Contingency	0.26	0.26	0.26	3

Notes:

1. Based on guidance in Perry and Green (1997). Minimum and Maximum reflect the range given in the reference, Best is the average of those values. The costs for Major Equipment are multiplied by this factor to make an allowance for equipment not yet identified.
2. 2/3 of the factor used for installation of equipment for a fixed solids processing facility. Assembly of plant following relocations is accounted for in Facility Relocation table. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
3. Used Factors from Table 9-51 of Perry and Green for solids processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
4. Used factors from Table 9-51 of Perry and Green (1997) for solids-fluid processing. Minimum and Maximum reflect the range given in the reference table, Best is the average of those values. Costs are estimated by multiplying the Major Equipment + Allowance costs by this factor.
5. Initial start-up costs are taken from Equation 9-260 of Perry and Green. The Direct Plant costs are multiplied by this factor to estimate start-up costs. Minimum and Maximum values reflect possible ranges for the newness of the process, newness of the equipment, the labor quality, and the interdependency of steps in the process. The Best factor is an average of the Minimum and Maximum.

4.2 Monofill

For all scenarios in this cost estimate except long-term storage, treated mercury will be disposed of in a monofill. The monofill is a single purpose landfill: only treated mercury will be placed in it. Since it will hold waste containing mercury, the monofill will be designed, constructed, and operated as a hazardous waste disposal facility.

4.2.1 Monofill Requirements per Code of Federal Regulations

The bases for requirements that will affect the monofill are taken from 40 CFR Part 264 (CFR 2004). These requirements are summarized below.

Design Features

The monofill will require a double liner on the bottom, a final cover that includes a top liner, a leachate collection and removal system, and a leak detection system (§264.301). The secondary part of the bottom liner must be composite (soil or clay plus a membrane), with a three foot thick soil/clay component. The top liner is installed upon closure of each fill cell. The top liner must minimize liquids that migrate into the landfill, promote drainage away from the sealed landfill, and include cover to protect the liner (§264.310).

The monofill must have a run-on control system that prevents water from flowing onto the active portion of the fill during a storm. The monofill also must have a run-off control system to collect water that falls into the fill during storms. Both systems require facilities to empty water out following storms.

Construction Quality Assurance

A Construction Quality Assurance (CQA) program will be required (§264.19). This entails preparing a written CQA plan developed and implemented by a registered Professional Engineer. Testing and inspections are required to ensure that construction materials and installed unit components meet the design specifications. Sufficient observations, testing, measurement, and inspections are required to ensure:

- Structural integrity of foundations, dikes, soil liners, geomembranes, leachate collection and removal systems, and leak detection systems;
- Proper construction according to design specifications and permits; and
- Conformity of materials with design and material specifications.

The CQA program will also require test fills for compacted soil liners to ensure the liners meet requirements, or data showing the liner will work in the site conditions.

Special Requirements for Containers

Containers must be at least 90% full when placed in the landfill (§264.315).

Waste Analysis

If the landfill is located at a different site than is the waste treatment facility, the landfill operator must inspect or analyze each shipment to ensure it matches the manifest (§264.13).

Security

The facility must be secured with 24-hour surveillance or a fence and gate attendant (§264.14).

Personnel Training

Personnel who work at the landfill must undergo hazardous waste handling training (§264.16).

Monitoring and Inspection

During construction, the liners must be inspected to ensure their integrity (§264.303). While in operation (filling), the landfill must be inspected weekly and after storms to detect:

- Problems with the run-on and run-off control systems,
- Problems with the leachate collection and removal system, and
- Leaks as shown in the leak detection system.

If leakage rates increase above the “actionable level”, then a response is required (§264.304).

Post-Closure Care

The final cover will have to be maintained to ensure its integrity and effectiveness. Repairs may be necessary to correct the effects of settling, erosion, or other events (§264.310).

The leachate collection and removal system must be operated until leachate is no longer detected. Once the final cover is installed, the leak detection system will have to be checked monthly to ensure that no leaks are occurring. If leak rates are slow enough, the interval can eventually be increased to semi-annual inspections. If leakage rates increase above the “actionable level”, then response is required (§264.303).

A groundwater monitoring system must be maintained and monitored.

Post-closure care must continue for thirty years after the monofill is closed (§264.117).

4.2.2 Monofill Cost Bases

Monofill costs are estimated for the various treatment scenarios. Costs are estimated based on a disposal cell that is sized to hold five years’ worth of treated mercury. Since the processes assumed for these cost estimates treat 1,000 tons of mercury per year, each cell holds 5,000 tons. Consequently, the cost estimates for 25,000 ton scenarios have five monofill cells.

For centralized treatment, it is assumed that the treatment facility and monofill are located at a commercial site that already has landfills. Thus, the operator of the existing landfill can readily apply for expansion to include the monofill. Similarly, for the mobile treatment case, the waste (in drums or tubes) is transported to a centralized monofill at a site where the operator already has landfills. In both cases, existing buildings are assumed to be available for administrative and other uses associated with the disposal cells for treated mercury.

The monofill design, construction, operation, and post-closure care are based on the requirements of 40 CFR Part 264 which are listed in Section 4.2.1. How the requirements are incorporated in the landfill design envisioned for the cost estimate is discussed below.

General Design Features

For the fixed treatment facility alternative, it is assumed that a monofill will be located at the treatment site. For the mobile facility alternative, it is assumed that material will be transported to a centralized monofill following treatment.

For the purposes of the estimate, it is assumed that the monofill will be divided into cells that are large enough to hold five years' worth of treated waste. The size of the cells will vary depending on whether the waste is placed in drums or macroencapsulated in Arrow-Pak tubes. The number of drums or tubes per year (and thus the size of the cell) is calculated based on the assumptions for each scaled-up treatment process. Figure 4-4 shows a plan and cross-section view for a monofill cell.

The exact design requirements will depend on Factors such as the weather, hydrology, soil conditions, and topography of the landfill site. The design used for this cost estimate includes features identified for a hazardous waste landfill by USEPA (2003), Geoengineers (2004), Jones (2003), Rocky Mountain Arsenal (2004), and DPRA (1998). This design meets the CFR requirements discussed in Section 4.1.5.1. As required by the CFR, each monofill cell will have the following features:

- Run-on controls in the form of a 6-foot high berm,
- Run-off controls in the form of a 6-foot deep drainage ditch,
- A two layer bottom liner,
- A top liner once the cell is closed, and
- Groundwater monitoring wells.

Disposal Volume Excavation

The landfill is constructed such that half the waste volume is below existing grade, and the remainder is built-up in a mound above grade. The required volume of material to be excavated for each cell is based on the assumed depth and required cell area.

Run-on and Run-off Controls

Each monofill cell will be surrounded by a run-on control berm and run-off control ditch. The excavation volume is based on a 6-foot deep, trapezoidally shaped ditch with a 1-foot wide base. The berm is assumed to be 6-feet high.

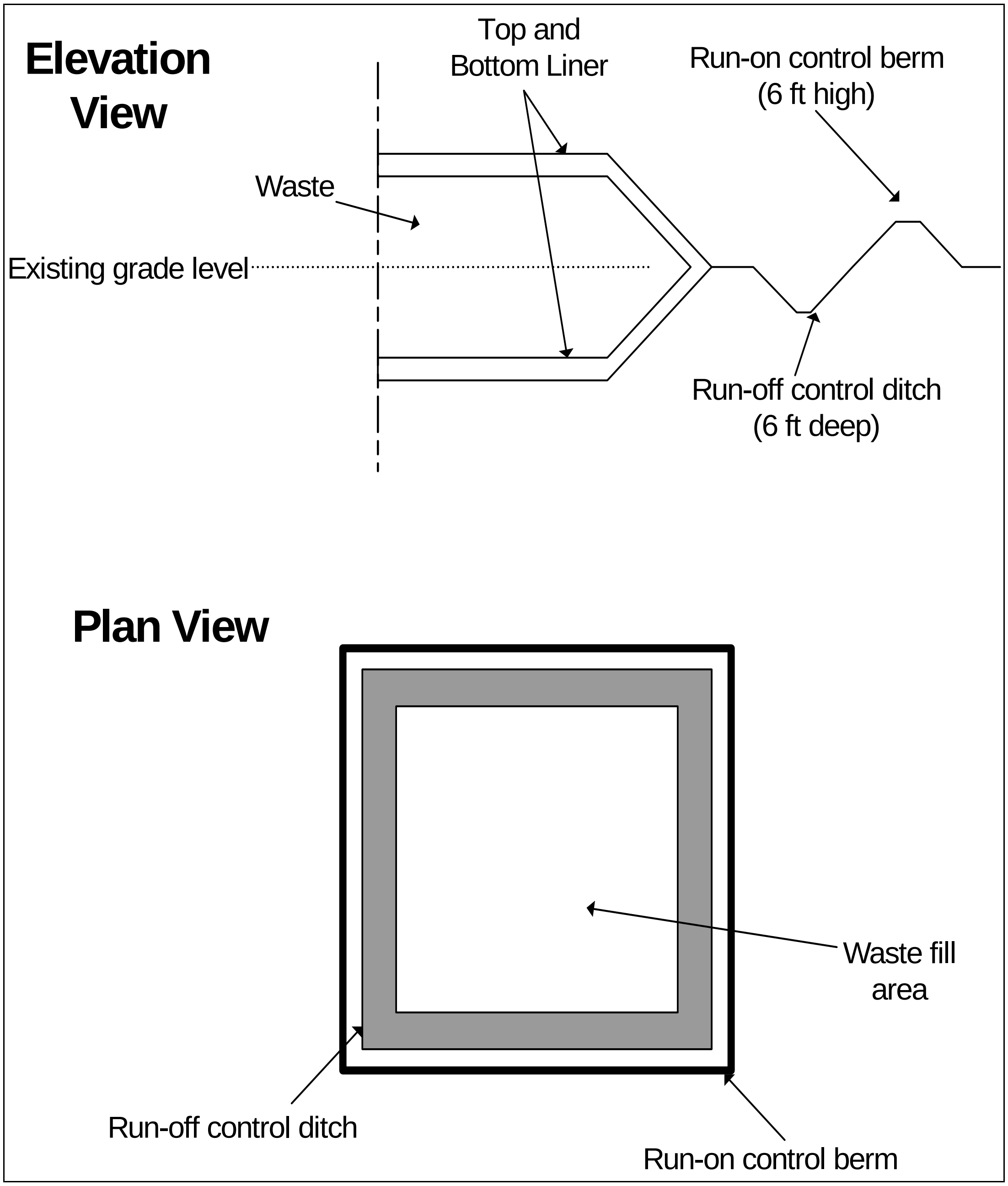


Figure 4-4. Landfill Cross-Section and Plan Design

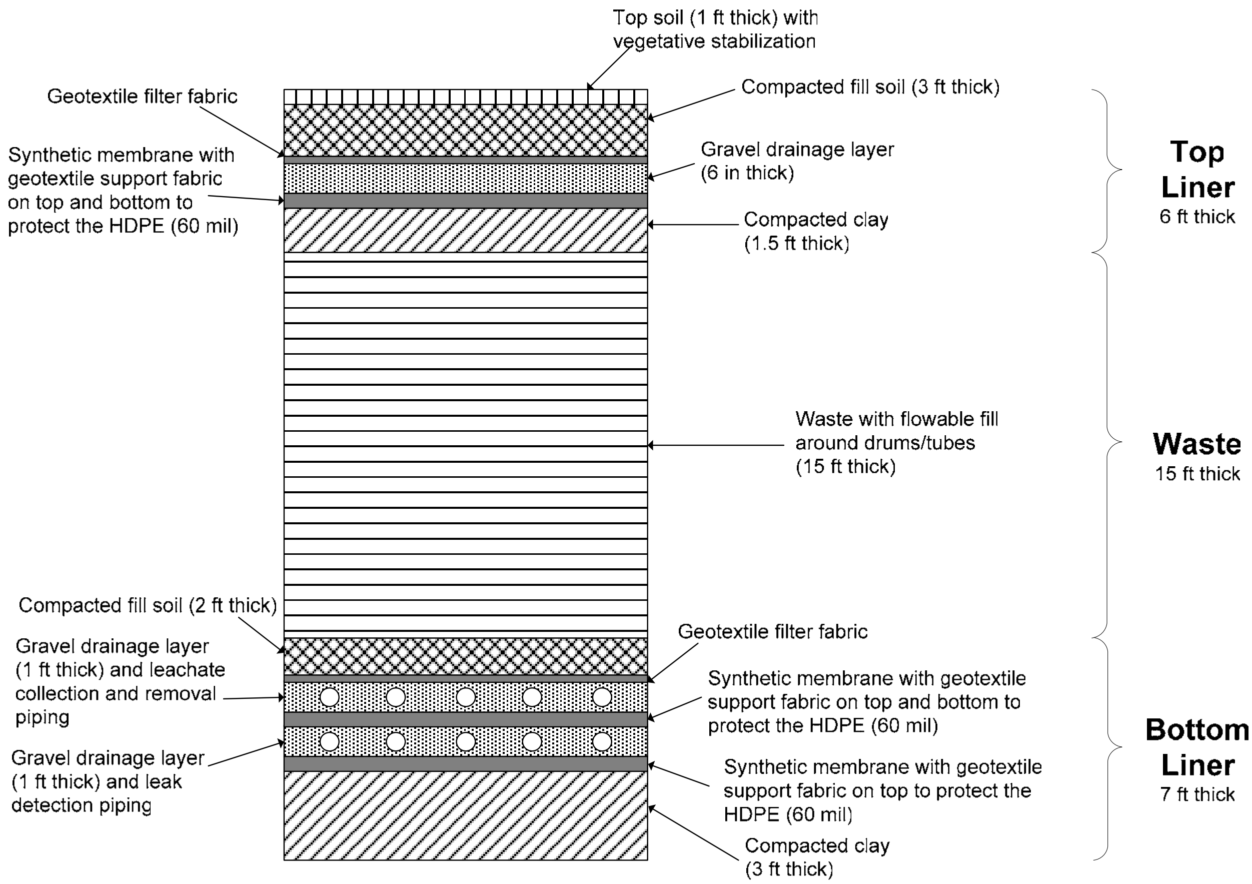


Figure 4-5. Landfill Liner Cross-Section

Waste and Fill Layer

Two feet of compacted fill soil will protect the primary bottom liner from damage during placement of the waste containers. As waste is placed in the monofill, a flowable fill will be placed around the drums or tubes. The fill will be treated to the desired pH for the waste. The waste layer will be fifteen feet thick.

It is assumed that 10% of the disposal volume will be filled with flowable fill. The flowable fill unit cost is based on the value for compacted clay.

Top Liner

Once the waste layer is full, a cover will be placed to close the cell. This top cover will consist of a composite liner with 1.5 feet of compacted clay and a HDPE membrane. Geotextile support fabric will sandwich the HDPE to protect it. A gravel drainage layer will promote drainage of rain away from the sealed fill cell. Geotextile filter fabric will prevent fill soil from clogging the drainage layer. Top soil will be placed above compacted fill soil that will protect the top cover. Vegetation will be planted to prevent erosion of the top soil and fill soil.

Groundwater Monitoring Wells

Each fill cell will have four groundwater monitoring clusters (one upgradient cluster and three downgradient based on the design in DPRA (1998). Each cluster consists of three wells.

Construction Quality Assurance

For the cost estimate, the CQA Program will add to construction expenses. This additional cost is meant to cover all observations, tests, measurements, and inspections required during construction to assure quality.

Special Requirements for Containers

All three treatment processes considered in this estimate will fill containers at least 90% full, so the CFR requirement will be met.

Waste Analysis

It is assumed that the operator of the landfill will be able to inspect markings on the outside of the drums or tubes to verify the contents of the containers. Quantities of these barrels or tubes will easily be checked by the logistics personnel when shipments of waste arrive. The chemical analysis of the waste that occurs at the treatment facility will serve as the analysis for the landfill also.

Equipment

Since the monofill is located at an operating landfill site, all equipment necessary for handling waste and fill is assumed to be available. This equipment may include cranes, front end loaders, and flowable fill equipment. No costs are charged to the monofill to purchase, operate, or maintain this equipment.

Security and Personnel Training

It is assumed that the landfill will be constructed at a site that already has a security system, so this cost will not be included in the estimate. It is also assumed that the personnel who work the new landfill will already have hazardous waste training.

Staffing

Since the monofill will be located at a site that already has landfills, the staff available at the site will be utilized for monofill operations (during filling). The charges for landfill site staff time will depend on the volume of waste delivered from the treatment process and the frequency that waste is shipped to the monofill. The staff that will be utilized is assumed to consist of:

- Four Operators,
- One Maintenance Technician,

- One Logistics and Shipping Clerk,
- One Operations Supervisor,
- One Administrative Assistant,
- One Plant Manager,
- One QA/Health/Safety Coordinator.

Monitoring and Inspection

During construction, the liners will be inspected as part of the CQA Program. The run-off, run-on, LCRS, and LDS will be inspected weekly during operations (filling). The cost of these inspections is included in the charges for the QA, Health, and Safety Coordinator.

Leachate Treatment

While in operation (filling), the LCRS will collect rain water that falls in the open cell. It is assumed that this leachate will not require treatment.

Utilities

Utilities are assumed to be an annual cost for each cell during filling operations. Once cells are closed, the utilities are assumed to be negligible.

Post-Closure Care

The post-closure care period will be 30 years following closure of each landfill cell.

It is assumed that the LCRS will require monthly inspections for five years following closure. Five years after cell closure, it is assumed that no more leachate will appear and that inspections are not required. Each inspection is assumed to require a day of an operator's time.

The LDS is assumed to require monthly inspections until 5 years after closure, then semi-annual inspections for the remainder of the 30-year post-closure care period. Each inspection is assumed to require a day of an operator's time.

It is assumed that ground water samples will be required monthly from each well while cells are being filled, and then semi-annually for the 30-year post-closure care period.

Permits and Bonding

Permits are assumed to be an annual cost for the entire operation and post-closure period for each landfill cell.

Bonding is assumed to be an annual cost for the entire operation and post-closure period for each landfill cell.

Assumptions on Failures, Leakage Rates, and Corrective Actions

Since the costs for catastrophic failures and corrective actions are difficult to estimate and could be high, the following assumptions will be made:

- It is assumed that no problems will be found during operation (filling) that require repairs or remediation.
- Leakage rates are assumed to remain below "actionable levels", so that repair and remediation is not required during the life of the monofill.
- It is assumed that no ground water problems occur that require repair of the monofill.
- It is assumed that no catastrophic failure of the containment system occurs that requires emergency repair.

4.2.3 Monofill Costs

Tables showing the build up of the cost estimates are provided in Appendices E, F, and G for monofills that take treated mercury from the Option A, Option B, and Option C processes, respectively. Each of the Appendices contain the following:

- A table of monofill dimensions
- A table of labor and materials costs during construction
- A table of O&M costs during filling
- A table of post-closure O&M costs

Engineering

Engineering costs are estimated as being 10% of the Construction costs (DPRA 1998).

Construction

Construction costs are the sum of Labor and Materials, Inspection and Testing, Quality Assurance, Other Field Expenses, Fee, and Contingency. Inspection and Testing, Quality Assurance, and Other Field Expenses are estimated as percentages of the labor and material costs. The Fee and Contingency are estimated as percentages of the sum of all other Construction costs. The factors, taken from DPRA (1998), are shown in Table 4-15.

Table 4-15. Factors Used to Estimate Monofill Construction Costs

Cost Element	Factor Used in Cost Estimate
Inspection and Testing	0.05
Quality Assurance	0.15
Other Field Expenses	0.05
Fee	0.15
Contingency	0.10

Operating and Maintenance During Filling

Operations and Maintenance costs during filling are assumed to be made up of the following categories: Permits, Bonding Insurance, Direct O&M Costs, and Contingency. Permits cost $10,000 per year (DPRA 1998). Bonding Insurance is assumed to cost $10,000 per year. Direct O&M Costs are calculated in a separate table; the subtotal is given in the Summary table. Per DPRA (1998) Contingency is 10% of the other O&M costs.

An annual total is given for O&M during filling. The subtotal for O&M during filling sums the annual total for the number of years treated mercury is sent to the monofill: 5 years for 5,000 tons, 12 years for 12,000 tons, and 25 years for 25,000 tons.

Operating and Maintenance Post-Closure

Operating and Maintenance costs for the 30 years after each monofill cell is closed are given in Appendices E, F, and G. Details of the estimate are given in the O&M (post-closure) table. The O&M (post-closure) table gives the costs for one cell. Consequently, the summary table results for scenarios that require more than one cell are multiples of the O&M (post-closure) table total.

Miscellaneous

The size of the monofill cell is a key parameter for estimation of labor and materials costs. The Dimension tables in Appendices E, F, and G give the size of a five year monofill cell for each treatment process. The size of the cell is set by the number of barrels of treated mercury the five year cell must accept. Dimensions are calculated for disposal of treated mercury in barrels and in Arrow-Pak tubes.

The monofill is assumed to be shaped as shown in Figure 4-4, with a square or rectangular plan. The cross-sections at the edges of the cells have 45-degree slopes. Volumes and areas for cost estimation are approximated using these shapes and the lengths of the cell sides.

The cost estimates for labor and materials are based on the size of the five year cell and the unit costs for the materials and construction activities. All unit costs are installed costs based on DPRA 1998. Since this reference has 1998 prices, the costs have been escalated 12%[20] to account for inflation between 1998 and 2004 (USDOL 2004).

Direct Operating and Maintenance costs during filling are calculated in the Direct O&M (filling) tables in Appendices E,F, and G. The total from this table is used in the Summary table. The direct costs are composed of the following: salary for staff, costs for groundwater monitoring tests, utilities, and the fee. Salary for staff is based on an estimate of the time required to accept shipments of treated mercury. The number of shipments is calculated based on the amount of waste produced per year, the weight each truck can transport, and the amount of room available on each truck. The number of shipments is calculated for treated mercury in barrels and for waste macroencapsulated in Arrow-Pak tubes. Annual utilization of the staff is calculated as the ratio of shipments to shifts the staff works (based on a five-day work week). The burdened salary for staff is taken from Salary.com.

The cost for groundwater monitoring tests is based on costs given in DPRA (1998). The costs have been inflated 12% to account for inflation between 1998 and 2004 (USDOL 2004).

Utilities are assumed to cost $10,000 per year while the monofill is in operation (being filled).

The fee is 15% of the sum of the other operating and maintenance costs.

The O&M (post-closure) sheets in Appendices E, F, and G gives the total costs for operating and maintenance for a 30-year post-closure period. These costs are made up of the following parts: LCRS monitoring, LDS monitoring, ground water sample analysis, utilities, contingency, license and bonding costs, and the fee.

LCRS and LDS monitoring costs are a function of the time spent monitoring the systems per year and the costs for operators' time to perform the monitoring. Each inspection is assumed to take one day of an operator's time. The cost for a day of an operator's time is estimated as a function of the burdened salary for the operator.

The cost for groundwater monitoring tests is based on costs given by DPRA (1998). The costs have been inflated 12% to account for inflation between 1998 and 2004 (USDOL 2004).

Utilities are assumed to cost $1,000 per year after the monofill cell is closed. License and bonding fees are assumed to cost $10,000 per year after the monofill cell is closed.

The fee is 15% of the sum of the post-closure operating and maintenance costs. Contingency is calculated as 10% of the post-closure operating and maintenance costs plus fee.

4.3 Storage

This section first lays out assumptions for calculating the costs of the long-term storage alternative, and then describes assumptions for the costs associated with the treatment alternatives. The basic input data are derived from Appendix D of the MMEIS (DLA 2004). For example, the MMEIS estimates the annual cost of storing 2,617 MT of elemental mercury at the Somerville Depot to be $404,495. This is made up of two parts, utility costs of $4,945 and rental of $400,000, based on 43,200 ft^2 at an annual rent of $1.76/$ft^2$. Routine maintenance of the warehouse is assumed to be included in the rent. Other labor, such as walking down the stockpile and taking occasional mercury vapor concentration measurements, is assumed to be negligible. Thus, the cost of storage of 1 MT at Somerville for 1 year is $404,495/2617 = $154. The average cost of storage at all DLA facilities (except the Y-12 facility) is $147/MT/yr. In the calculations reported below, the cost of storage is simply calculated by multiplying the amount of elemental mercury in storage in a particular year by $147, discounting to obtain NPV, and summing over all years of storage.

[20] Using Producer Price Index average for 1998 versus the average through August 2004.

4.3.1 Long-Term Storage

This subsection describes the bases and assumptions for long-term storage of elemental mercury for the three mass alternatives.

Alternative 1 – 5,000 MT

Alternative 1 is quite close to the status quo at DNSC locations. Therefore, Alternative 1 is costed as if storage will continue there for 35 years. On a non-discounted basis, 5,000 MT would therefore cost 5,000x147 = $735,000/year.

Alternative 2 – 12,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 7,000 MT becomes available at a uniform rate over a period of 12 years, i.e., at a rate of 583 MT/yr[21]. For the storage alternative, therefore, the amount in the stockpile will increase by this amount each year, and additional (non-discounted costs) accrue at a rate of 583×147 = $85,700/yr. This is in addition to the costs incurred for storing the original 5,000 MT.

Alternative 3 – 25,000 MT

For this alternative, it is assumed, as for Alternative 1, that there is 5,000 MT of elemental mercury in existing storage. The remaining 20,000 MT becomes available at a uniform rate over a period of 25 years, i.e., at a rate of 800 MT/yr. For the storage alternative, therefore, the amount in the stockpile will increase by this amount each year, and additional costs will accrue at a non-discounted rate of 800×147 = $117,600/yr.

4.3.2 Storage Costs Associated with Treatment and Disposal Alternatives

The need for storage will not vanish immediately even if the waste is treated.

Alternative 1 – 5,000 MT

For the centralized treatment location, it is assumed that elemental mercury will be transported from the current storage locations to the treatment facility at a rate of 1,000 MT per year for five years. Each 1,000 MT occupies 45,000 ft^2 (~ 4,200 m^2). It is assumed that storage space will be decommissioned at a rate of 45,000 ft^2 (4,200 m^2) per year, and that storage costs will decrease by 1,000x147 = $147,000/yr until all the mercury has been treated. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

Alternative 2 – 12,000 MT

When the mercury is treated at a centralized facility, it is assumed that the 583 MT/yr of "new" elemental mercury is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining 417 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Each year, therefore, the non-discounted costs of storing elemental mercury decrease by 417x147 = $61,300/yr for 12 years. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

Alternative 3 – 25,000 MT

When the mercury is treated at a centralized facility, it is assumed that the 800 MT/yr is transported directly to the treatment facility, thus obviating the need for intermediate storage. The remaining

[21] Note that the assumption that there is about 5,000 MT in existing storage and that additional elemental mercury becomes available at a rate of a few hundred MT per year is consistent with data in Appendix D of the MMEIS.

200 MT/yr required to make up the assumed treatment rate of 1,000 MT/yr is drawn down from storage. Each year, therefore, the non-discounted costs of storing elemental mercury decrease by 200x147 = $29,400 for 25 years. The same rate of depletion of the existing stockpile is assumed for the mobile treatment alternative.

4.4 Transportation

This section describes the assumptions and bases for transportation costs associated with the various treatment and storage alternatives.

4.4.1 Centralized Treatment

In the case of centralized treatment, in all scenarios elemental mercury needs to be transported to the centralized facility at a rate of 1,000 MT per year. As noted above, it is assumed that elemental mercury will be transported in drums (six 76 lb (34 kg) flasks to a drum) with five drums to a pallet. Each pallet carries almost exactly 1 MT of elemental Hg: therefore 1,000 pallets will be transported each year. If the material is transported by road, each truck can carry up to 14 pallets or 14 MT (DLA 2004), so that there will be 71.4 truckloads per year. If the material is transported by rail, each railcar can carry up to 28 pallets or 28 MT (DLA 2004), so there will be ~ 36 railcar shipments per year. For the purposes of the current analysis, only full trucks or railcars will be considered. In practice, the exact number of pallets per truck or railcar is not critical because the authors used the MMEIS (DLA 2004) to calculate a cost per ton-mile of elemental mercury transport. These costs lie in the range $0.025-$0.038/MT-mile for rail and $0.039- 0.064/MT-mile for road. In addition to the cost per ton-mile, there is a preparation cost per ton that covers such items as overpacking, amounting to ~ $96/MT for truck transportation and ~ $111/MT for rail transportation.

The required transportation distances are not known because the location of the treatment facility has not yet been identified. To gain insight into the magnitude of mercury transport costs, three "proxy" and three existing storage depot locations were incorporated as candidate treatment facility locations. Transit distances were then calculated to the candidate treatment sites and unit transport costs derived from the MMEIS (DLA 2004) were applied to arrive at total transport costs. The six candidate site locations were chosen to provide a range of potential transport distances of 150 to 2,800 miles for "legacy" mercury stocks. Another basic assumption is be that the average transportation distance for "new" mercury is 1,000 miles and uncertainty will be accommodated by assuming that the range is 500 to 1,500 miles.

Examples of how transportation costs are calculated for the centralized treatment alternatives follow:

5,000 MT

For the 5,000 MT case the elemental mercury is all "legacy" mercury and therefore travels 150 to 2800 miles. The minimum non-discounted cost per year is to move 1,000 MT 150 miles by rail at a cost of $0.025 per MT-mile plus $111/MT preparation costs = 1,000x150x0.025+1,000x111 = $114,750/yr. The maximum cost is to move 1,000 MT 2,800 miles by truck at a cost of $0.064 per MT-mile and an initial preparation cost of $96/MT = 1,000x2,800x0.064 + 1,000x96 = $275,200/yr.

12,000 MT

For the 12,000 MT alternative, there is a need to transport 417 MT of "legacy" mercury and 583 MT of "new" mercury/year. The non-discounted annual costs for the legacy mercury are obtained by scaling the results from the previous paragraph by 0.417 to give a range from $47,900 to $114,800/yr. The minimum cost of transporting the "new" mercury is to move it 500 miles by rail at $0.025/MT-mile with $111/MT preparation costs = 500x0.025x583 + 111x583 = $72,700/yr. The maximum cost is to move the "new" mercury 1,500 miles by truck at a cost of 0.064/MT-mile and a preparation cost of $96/MT =

1,500x0.064x583 + 96x583 = $111,900/yr. Combining the estimates for “legacy” and “new” mercury gives a range of $120,600 to $226,700/yr.

For the centralized treatment alternatives, it is assumed that the monofill is collocated with the treatment facility and that transportation costs for the final waste form are negligible.

4.4.2 Mobile Treatment

In the case of mobile treatment, the treatment facility travels to the mercury, so no elemental mercury is transported. Instead, the treated waste (macro-encapsulated or not) is transported to a centralized monofill. If it is not macro-encapsulated, it is assumed that the waste is in 55-gallon drums for the Option A and Option B processes and 22 gallon drums for the Option C process. If it is macro-encapsulated, 55-gallon or 22-gallon drums are placed in sealed polyethylene tubes. The location of the monofill is not specifically known, so as in the centralized treatment scenarios, three “proxy” and three existing storage depot locations were incorporated as candidate monofill locations. Transit distances were then calculated to the candidate monofill sites and unit transport costs derived from the MMEIS (DLA 2004) were applied to arrive at total transport costs. The six candidate site locations were chosen to provide a range of potential transport distances of 150 to 2,800 miles for “legacy” mercury stocks. Again, it is assumed that the average distance to the monofill for waste forms generated from “new” mercury is 1,000 miles, with a range extending from 500 to 1,500 miles. The costs per MT-mile for treated waste are assumed to be the same as those for elemental mercury, so that transportation costs for mobile treatment can be simply scaled from those for centralized treatment. Thus, for example, for Option A, 3 MT of waste are generated for every MT of elemental mercury so, taking the 5,000 MT results from Section 4.4.1 and multiplying by 3 gives a non-discounted cost range from $344,000 to $825,600/yr

4.4.3 Long-Term Storage – Transportation of Elemental Mercury

For the 5,000 MT alternative, it is assumed that there is already 5,000 MT of elemental mercury in storage, so that no further transportation costs are incurred. For the 12,000 MT alternative, 583 MT of “new” elemental mercury is transported to a centralized storage facility each year for 12 years. For the 25,000 MT alternative, 800 MT of “new” elemental mercury is transported to a centralized storage facility each year. As above, the total transportation distance varies from 500 to 1,500 miles. For example, the range of costs for the 12,000 MT alternative (583 MT of “new” mercury per year) has already been calculated in Section 4.4.1 and is from $72,700 /yr to $111,900/yr.

4.4.4 Miscellaneous

There are a number of items that need to be delivered to the various sites and in principle their transportation costs should be calculated:

- Mercury flasks and 30-gallon drums for overpacks
- 22-gallon and 55-gallon drums to contain waste
- Reagents

In practice, the costs of these items are quoted as delivered to the site, so there is no need for explicit calculation of transportation costs.

4.5 Uncertainties

This section contains a simplified assessment of uncertainties in the costs associated with each of the 39 alternatives. The overall costs are broken down into the following categories:

As noted at the beginning of Chapter 4, each of the thirty-six cost estimates for treatment and disposal includes the following elements:

- Capital costs for the treatment facility,
- Capital costs for the macroencapsulation facility (if part of the alternative)
- Operating and maintenance costs for the treatment process,
- Operating and maintenance costs for the macroencapsulation process (if part of the alternative),
- Costs associated with the mobile treatment alternative,
- Transportation costs associated with each alternative,
- Costs of storing elemental mercury prior to treatment
- Decommissioning costs for the treatment facilities,
- Monofill engineering and construction costs,
- Monofill operating costs, and
- Costs of maintaining and monitoring the monofill for a thirty-year period following its closure.

Each of the three storage alternatives contains the costs of maintaining the existing stockpile (assumed to be 5,000 MT) in storage, adding to storage space for the 12,000 MT and 25,000 MT cases, and transporting elemental mercury to the storage facility(ies).

Initially, it was hoped that the uncertainties in each of these elements could be built up from uncertainties in the costs of individual components or activities. This did prove possible for the capital costs for fixed treatment and fixed macroencapsulation facilities. However, with the information that the team was able to collect within the budget available for this project, this did not prove possible for the remaining elements. Therefore, the authors adopted some simplifications, as will become clear after first considering some relevant background information.

4.5.1 Background Information on Uncertainties in Capital Costs and Life Cycle Cost Estimates

This section provides information on construction cost uncertainties from a commercial source and on life cycle cost estimate uncertainties from EPA.

4.5.1.1 Construction Projects/Capital Costs

Broadly speaking, there are five types of cost estimate for construction projects (Industrial Cost Engineering 2003)

- Conceptual or order of magnitude
- Factored
- Study or preliminary
- Basis of budget
- Detailed or Firm Price Construction

Conceptual: A minimum of information is used to develop this type of "Ball Park Estimate." The estimate is prepared from in house data available from past jobs on similar plants. A cost estimate determined this way is only valid for a similar plant. This estimate has a probable accuracy of -50% to +50% or worse.

A **factored estimate** requires that all process equipment must be priced. A factored estimate is produced by taking the cost of individual types of process equipment, and multiplying it by an "installation factor" to arrive at the Total Direct Process Cost. The accuracy of this type of estimate depends upon the definition of scope, equipment costs, and known process factors. This type of estimate has a probable accuracy of -25% to +30%.

A **study or preliminary estimate** is prepared after the process engineers have completed the conceptual design, made the equipment list by size and category, made preliminary process flow diagrams, and when engineering is from 1% to 10% complete. The following documents serve as the basis for this type of estimate:

- Reasonably defined equipment list by size and category, including onsite and offsite equipment.
- Preliminary overall plot-plans.
- Know general site conditions such as location, utility requirements, site survey, utility distribution (sewers, power feeders, etc.) labor productivity availability of skilled workmen, and availability of construction materials.
- Overall process flow diagrams.

The probable accuracy of this type of estimate is -15% to +20%.

A **basis of budget estimate** is prepared after the process engineers have completed the conceptual design, made an equipment list by size and category, made process flow diagrams, and the detail engineering is from 25% to 50% complete. The probable accuracy of this type of estimate is -10% to +15%.

In a **detailed estimate** each item is costed in a thorough manner without "eyeballing", "percentaging", or other forms of educated guesses. This estimate is prepared after the process design has been completed and when the detail design is 70% - 90% complete. The probable accuracy of this type of estimate is -5% to +10%.

4.5.1.2 EPA Guidance on Uncertainty in Life Cycle Cost Estimates

EPA has produced some guidance for Life Cycle Cost Estimates for Superfund remediation activities (USEPA 2000) – see Figure 4-6. This displays a similar pattern of declining uncertainty as the design becomes more complete and the project moves into construction and then O&M.

4.5.2 Uncertainties in Costs of Elements of the Long-Term Disposal of Elemental Mercury

Various parts of the cost estimate for the 39 alternatives for long-term disposal of mercury are at different stages with respect to the level of cost uncertainty.

Capital Costs for the Fixed Treatment Facilities: per the information above from the Industrial Cost Engineering Web site, it would appear that a study or preliminary estimate is feasible because overall process flow diagrams are available as is a reasonably defined equipment list. General site conditions may not be known, but it is assumed that the facility will be constructed at an existing site and that adequate utilities, labor and materials will be available. In addition, these facilities are quite simple and it is not expected that there will be very large cost over or underestimates. Therefore, a probable accuracy in the range –15% to + 20% is expected.

Capital Costs for Fixed Macroencapsulation Facilities: It is also expected that a study or preliminary estimate is possible for these facilities so that a predicted range of –15% to +20% is reasonably in accord with expectations.

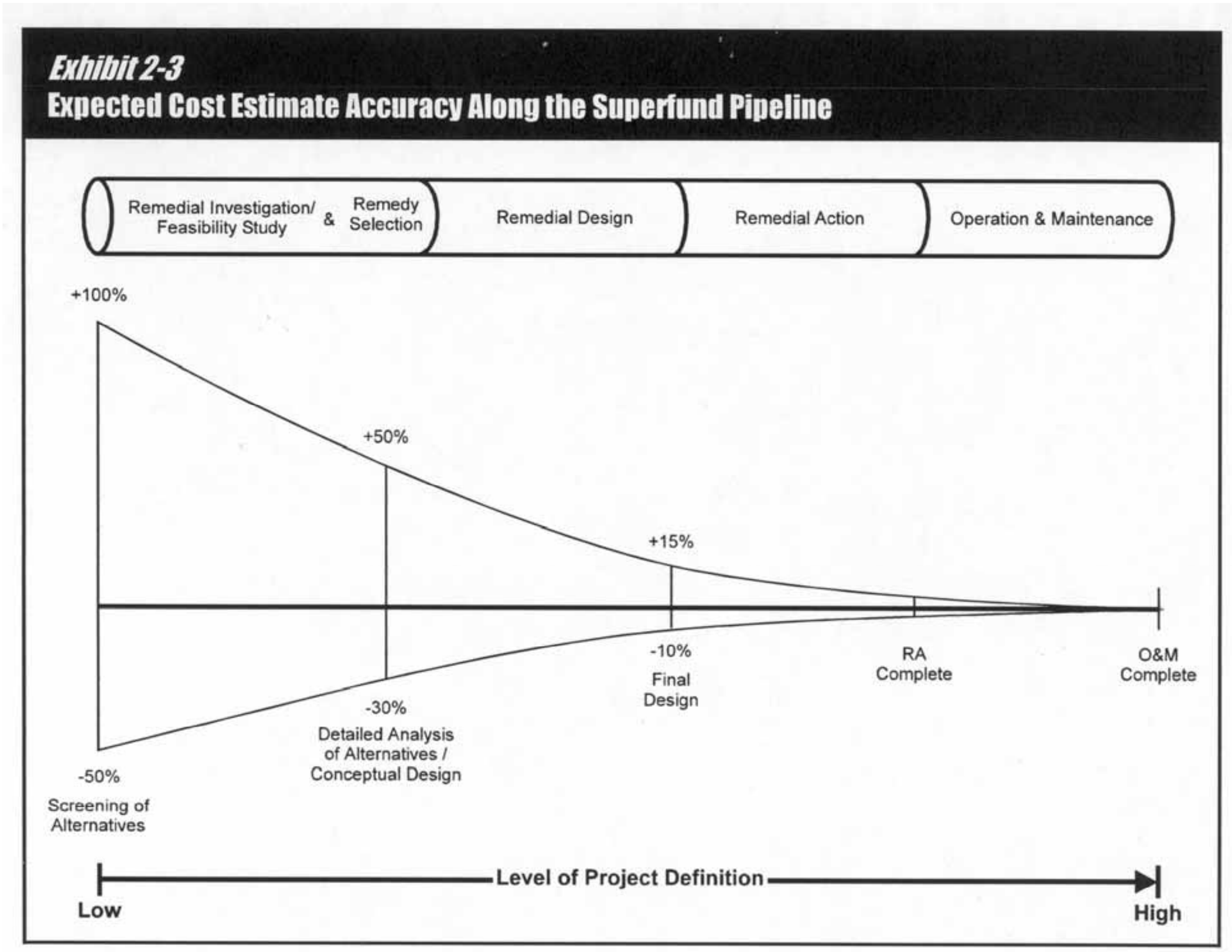


Figure 4-6. Expected Cost Accuracy Along the Superfund Pipeline: Exhibit 2-3 from EPA (2000)

Capital Costs for Mobile Treatment Facilities: this is an area of greater uncertainty. The cost of a single mobile unit can be confidently estimated to within –15 to +20%, as for the fixed case, but what is unknown is whether there would be a single large unit, two half-size units, or several smaller ones. The actual cost estimates in Appendices C and D are for one large facility. One could easily envisage the construction costs doubling or tripling if several smaller units were constructed. Therefore, the cost range is taken to be –15% to +200%.

Capital Costs for Mobile Encapsulation Facilities: these suffer from the same uncertainties as do the costs for the mobile treatment facilities and a similar range is assumed, -15% to +200%.

O&M Costs for Fixed Treatment and Macroencapsulation Facilities: referring to Figure 4-2 above, the fixed treatment and macroencapsulation facilities are beyond the conceptual design phase but clearly not at the final design phase. Interpolating between these two points on Figure 4-2 suggests that a range in these cost between – 15% and + 20% is reasonable.

O&M Costs for Mobile Treatment and Macroencapsulation Facilities: this alternative is really still at the pre-conceptual phase and per Figure 4-2. the range of uncertainty in costs is –50% to + 100%.

Decontamination Costs for the Treatment and Macroencapsulation Facilities: 50% of capital costs with same percentage uncertainty range.

Construction and O&M Costs for the Monofill: monofills are relatively well understood. Referring again to Figure 4-2, the monofill is between conceptual and final design so here again a range of cost uncertainty between –15% and + 20% is reasonable for the total Life Cycle Cost Estimate for the monofill.

Transportation Costs: the largest uncertainty in transportation costs is not knowing how far the mercury or the waste product will be transported. Other transportation costs are well documented in the Mercury Management Environmental Impact Statement (DLA 2004). Transportation cost estimates and uncertainty ranges are discussed in Section 4.4

Storage Costs: storage of elemental mercury has been studied in considerable detail in the MMEIS and is well known. Uncertainties should be small. The authors assigned a small range from –10% to +10%.

4.5.3 Calculation of Uncertainties

In summary, the input cost ranges for the uncertainty analysis are as follows:

- Capital costs for the fixed treatment facility and the fixed macroencapsulation facility: bottom-up calculation (see Appendices C, D, and E) – approximately –15% to + 20%
- Capital costs for the mobile treatment facility and the mobile macroencapsulation treatment facility: -15% to + 200%
- Operating and maintenance costs for the fixed treatment process and the fixed macroencapsulation process: -15% to + 20%
- Operating and maintenance costs for the mobile treatment facility and the mobile macroencapsulation facility: -50% to + 100%
- Transportation costs associated with each alternative: see Section 4.4
- Costs of storing elemental mercury prior to treatment (or for the storage alternative): -10% to + 10%
- Decommissioning costs for the treatment and macroencapsulation facilities: 50% of capital costs with same percentage uncertainty range
- Monofill Life Cycle Cost Estimate: -15% to + 20%.

These costs were assigned triangular probability distributions and were input into the Crystal Ball® computer model for Monte Carlo simulation (Decisioneering 2004), leading to estimates of uncertainty on the total costs of each alternative.

4.6 Results and Interpretation

The results of the economic analysis are summarized in Tables 4-16 and 4-17. Note that the "best" estimates are the means that result from the Monte Carlo analysis and are not necessarily exactly the same as would result from a sum of point estimates without uncertainty distributions. Tables 4-16 and 4-17 prompt a number of observations and conclusions.

Importance of Costs of Reagents

The most striking result is that the Option C alternatives cost far more than do the others. Analysis of the calculations reveals that there is one parameter that drives almost the whole of this difference – the cost of reagents. For Option C, the NPV of reagent costs alone over five years is approximately $123M. By contrast, the five-year NPV of reagents for the Option A process are approximately $8M over 5 years. For the Option B process, NPV of reagent costs over 5 years is approximately $1.4 M. Therefore, for the alternatives that treat 5,000MT, the reagent costs alone account for more than $100M difference between the costs of Option C process and those of the Option A or Option B processes, with correspondingly larger differences for the 12,000 MT and 25,000 MT alternatives.

The composition of the Option C reagents is proprietary. In any future decisionmaking process, the cost per kg of treated Hg will need to be examined in more detail.

Option B – Lowest Cost

The Option B process consistently exhibits the lowest costs. As noted above, it has the lowest reagent cost. In addition, it has the least mass increase of the three technologies – the mass multipliers for waste form production are 1.63 (Option B), 3.26 (Option A), and 5.66 (Option C). This affects other items such as transportation costs.

Mobile Treatment More Costly and More Uncertain

The best estimates for the NPV of alternatives that include mobile treatment are somewhat higher than those for alternatives that include treatment at fixed facilities. In addition, the uncertainty ranges are much wider. Both of these principally result from the wide uncertainty bands on mobile treatment alternatives: -15% to +200% for capital costs and –50% to + 100% for O&M costs. There are also extra costs associated with assembling and disassembling the equipment and moving it from site to site.

Narrow Range of Uncertainties for Fixed Facility Alternatives

In Table 4-16, the range of NPV numbers for fixed-facility alternatives appears to be quite narrow, -10% to +10% or even less. The reader may fairly ask whether these ranges are too small.

To a certain extent, these narrow ranges are an artifact of the Monte Carlo analysis. The input ranges of uncertainties are discussed in Section 4.5 and summarized in Section 4.5.3. There, the ranges chosen for most of the inputs to the Crystal Ball® uncertainty analysis of fixed facility alternatives are in the range –15% to +20%. It is a feature of Monte Carlo analyses that, at a given percentile level (e,g., 95th), the 95th percentile of a sum is less than the sum of the 95th percentiles of the inputs. The more a sum is broken down into its components, the more its 5th to 95th range of confidence is narrowed. Hence we see in Table 4-16 (again excluding the mobile treatment cases) the predicted percentage range has been narrowed to less than the input ranges of from –15% to + 20%.

One possible way of dealing with this would be to default to Figure 4-6. The project as a whole lies somewhere between the "Detailed Analysis of Alternatives/ Conceptual Design" and the "Final Design" which means that the uncertainty range could be as much as –30% to +50%, or as little as –10% to + 15%. The reader can then make a subjective choice as to exactly where in this range of ranges the project actually lies. Similarly, the reader might conclude that the authors have overestimated the maturity of the input items summarized in Section 4.5.3 and that the input ranges of uncertainties should be larger. In summary, there is a great deal of subjectivity in the uncertainty analysis and the reader is entitled to use his or her own judgment to conclude that the ranges might well be larger.

Modest Long-Term Storage Costs

The cost of storage is relatively modest. Note that these storage costs were derived from data in the MMEIS. For example, for continued storage of 5,000 MT for up to 35 years, the NPV is $11.6M. Continuing to store elemental mercury for years or even decades is a reasonable course of action.

It is pertinent to reiterate that, as far as possible, the long-term storage and disposal alternatives are treated on a comparable basis. All of the alternatives have storage requirements and these have been consistently costed by taking data on storage from the MMEIS. Transportation costs have also been treated consistently with data taken from the MMEIS. The periods of time considered are also consistent. For example, the treatment and disposal alternatives include the time taken to fill the monofill and thirty subsequent years of monitoring. Thus, for the 5,000 MT alternatives, costs for treatment and disposal are taken out to 35 years (5 years to fill the monofill and 30 years of monitoring). The costs for long-term storage of 5,000 MT of elemental mercury are also taken out to 35 years. For all alternatives, the NPV is calculated using the same discount rate, as provided by OMB.

Table 4-16. Net Present Value Estimates

Treatment Scenario			Net Present Value Estimates in Millions of Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]	**Min.**[a]	**Best**[b]	**Max.**[c]
Option A	With	Fixed	77.1	82.7	89.0	149	161	174	245	265	287
Option A	With	Mobile	75.8	99.2	128	143	191	251	232	315	415
Option A	Without	Fixed	60.2	65.4	71.3	117	128	141	184	203	224
Option A	Without	Mobile	57.7	79.8	107	105	150	207	169	242	341
Option B	With	Fixed	32.3	34.3	36.4	62.2	66.2	70.6	102	109	116
Option B	With	Mobile	32.4	40.9	50.7	60.5	78.3	97.5	98.4	127	160
Option B	Without	Fixed	22.7	24.3	26.2	42.8	46.1	49.9	69.6	75.2	81.8
Option B	Without	Mobile	22.3	29.3	38.0	40.9	54.2	71.7	65.1	87.5	118
Option C	With	Fixed	162	178	197	342	378	418	579	639	707
Option C	With	Mobile	138	203	292	290	429	617	490	732	1,040
Option C	Without	Fixed	146	163	181	306	341	381	517	578	647
Option C	Without	Mobile	119	184	270	247	386	573	421	656	967
Long-Term Storage [d,e]			10.4	11.6	12.8	26.1	29.0	31.9	51.3	57.0	62.7

a. Fifth percentile of the distribution derived from the Crystal Ball® analysis
b. Mean of the distribution derived from the Crystal Ball® analysis
c. Ninety fifth percentile of the distribution derived from the Crystal Ball® analysis
d. Not derived from Crystal Ball® analysis – best estimate based on MMEIS data (DLA 2004) with ±10% uncertainties
e. Cost of shipping elemental mercury to the storage location not included. Upper bound transportation costs derived from MMEIS data are \$0 (5,000 MT), \$1.0M (12,000 MT), and \$2.3M (25,000 MT). These are at most small percentages of the total cost of long-term storage.

Table 4-17. Net Present Value Estimates Expressed as Cost per Metric Ton of Treated Mercury

Treatment Scenario			Net Present Value Estimates in Dollars								
			5,000 Metric Tons			12,000 Metric Tons			25,000 Metric Tons		
Treatment Process	**Macro-Encapsulation**	**Fixed or Mobile Facility**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**	**Min.**	**Best**	**Max.**
Option A	With	Fixed	15,400	16,600	17,800	12,400	13,400	14,500	9,800	10,600	11,500
Option A	With	Mobile	15,200	19,800	25,600	11,900	15,900	20,900	9,300	12,600	16,600
Option A	Without	Fixed	12,000	13,100	14,300	9,800	10,700	11,800	7,400	8,100	9,000
Option A	Without	Mobile	11,600	16,000	21,400	8,800	12,500	17,300	6,800	9,700	13,600
Option B	With	Fixed	6,500	6,900	7,200	5,000	5,500	5,900	4,100	4,400	4,600
Option B	With	Mobile	6,500	8,200	10,100	5,100	6,500	8,100	3,900	5,100	6,400
Option B	Without	Fixed	4,500	4,900	5,200	3,600	3,800	4,200	2,800	3,000	3,300
Option B	Without	Mobile	4,500	5,900	7,600	3,400	4,500	6,000	2,600	3,500	4,700
Option C	With	Fixed	32,400	35,600	39,400	28,500	31,500	34,800	23,000	25,600	28,300
Option C	With	Mobile	27,600	40,600	58,400	24,200	35,800	51,400	19,600	29,300	41,600
Option C	Without	Fixed	29,200	32,600	36,200	25,500	28,400	31,800	20,700	23,100	25,900
Option C	Without	Mobile	23,800	36,800	54,000	20,600	32,200	47,800	16,800	26,200	38,900
Long-Term Storage			2,100	2,300	2,600	2,200	2,400	2,700	2,100	2,300	2,500

One difference between the treatment and disposal alternatives and the long-term storage alternatives is that permitting costs were only considered for the former. This is because the current stockpile of elemental mercury is not regarded as hazardous waste, and therefore hazardous waste permits are not required. For the treatment and disposal alternatives, costs accounted for non-discounted contributions of $10,000 per year for permitting (based on DPRA 1998) and an assumed $10,000 per year for Bonding Insurance. If it should become the case that storage of elemental mercury requires hazardous waste permitting and Bonding Insurance, a non-discounted amount of $20,000 per year should be added to the long-term storage costs. The additional 5-year NPV would be approximately $90,000, a small fraction of the $11.6M presented in Table 4-17.

In conclusion, all steps have been taken to develop costs for the alternatives on the same basis and for this reason it is a valid observation that long-term storage costs are modest relative to the costs of treatment and disposal.

5.0 REFERENCES

This chapter is divided into two parts. Section 5.1 provides a complete list of references. Section 5.2 lists those that were used in comparative analyses of Option Technologies A-F.

5.1 Complete List of References

AST 1998. *Macroencapsulation of Mixed Waste Debris at the Hanford Nuclear Reservation – Final Project Report by AST Environmental Services.* HNF-1846, Fluor Daniel Hanford, Richland, WA.

Bethlehem 2000. Bethlehem Apparatus Company Inc. *The Mercury Marketplace: Sources, Demand, Price and the Impacts of Environmental Regulations*. Presented at the Workshop on Mercury in Products, Processes, Waste and the Environment: Eliminating, Reducing and Managing Risks from Non-Combustion Sources. Baltimore, Maryland. Sponsored by U.S. EPA. March 22-23, 2000.

Bethlehem 2001. Bethlehem Apparatus Company, Inc., *Expression of Interest (for mercury processing)*, Hellertown, PA. July 6, 2001.

Bjästa Återvinning 2001. *Response to Defense Logistics Agency Request for Expression of Interest.* Business sensitive information removed.

Bjästa Återvinning 2002. *Bjästa Återvinning Company Information*. http://www.guru.se/bjasta/main.htm

BNL 2001. Brookhaven National Laboratory. *Response to Defense Logistics Agency Request for Expression of Interest*.

Bowerman, B. et al. 2003. *Using the Sulfur Polymer Stabilization/Solidification Process to Treat Residual Mercury Wastes from Gold Mining Operations*. (BNL-71499-2003-CP). In Society of Mining Engineers Conference, Cincinatti, OH, February 2003.

Bubb, J., MPR Associates 2004a. Memorandum of September 16, 2004 Telecon Conversation with J. Flatzinger, Weir Clear Liquid. *Vertical Acid Pump*.

Bubb, J., MPR Associates 2004b. E-mail to E. ten Siethoff, MPR Associates, September, 20, 2004. *Updated info BNL Mixer*.

Bubb, J., MPR Associates 2004c. Memorandum of September 16, 2004 Telecon with N. Perillo, Mokon. *Temperature Control Systems*.

Bubb, J., MPR Associates 2004d. Memorandum of September 8, 2004 Telecon with J. Meeker, Marion Mixers. *Mixer Price Quote*.

Bubb, J., MPR Associates 2004e. Memorandum of September 7, 2004 Telecon with J. Maranaville, Georgia Gulf Sulfur. *Industrial Sulfur Costs*.

Bubb, J., MPR Associates 2004f. Memorandum of September 10, 2004 Telecon with ERS Incorporated. *HDPE Pipe*.

Butz, J. 2004. E-mail and subsequent teleconference correspondence from Jim Butz (ADA) to Geoff Kaiser (SAIC) (and other EPA/ SAIC/ MPR staff), August 19, 2004.

CFR 2004. *Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities*. Title 40 Code of Federal Regulations, Part 264.

Chang, O. 2001. *Hazardous and Radioactive Waste Treatment Technologies*. CRC Press.

Davis, J.D. and C.R. Osucha (Nuclear Fuel Services) 1998. *Mercury Mixed Waste Treatment.* In 19th USDOE LLRMW Conference, Undated; circa 1998.

Decisioneering 2004. www.crystalball.com.

DLA 2004. Defense Logistics Agency. *Final Mercury Management Environmental Impact Statement*, Defense National Stockpile Center, Fort Belvoir, VA.

DOE 1994. U.S. Department of Energy. Gorin, A.H., J.H. Leckey, and L.E. Nulf. *Final Disposal Options for Mercury/ Uranium Mixed Wastes from the Oak Ridge Reservation*. Y/DZ-1106.

DOE 1998a. U.S. Department of Energy. *Polyethylene Macroencapsulation. Mixed Waste Focus Area.* Innovative Technology Summary Report, OST Reference No. 30. Prepared for Office of Environmental Management, Office of Science and Technology.

DOE 1998b. U.S. Department of Energy. *Macroencapsulation of Mixed Waste Debris at the Hanford Nuclear Reservation.* Final Project Report by AST Environmental Services, LLC. HNF-1846.

DOE 1999a. U.S. Department of Energy. *Mercury Contamination - Amalgamate (contract with NFS and ADA) Demonstration of DeHg[SM] Process. Mixed Waste Focus Area*, Innovative Technology Summary Report, DOE/EM-0471, prepared for Office of Environmental Management, Office of Science and Technology, September 1999. http://apps.em.doe.gov/ost/itsrtmwfa.html.

DOE 1999b. U.S. Department of Energy. *Mercury Contamination – Amalgamate (contract with NFS and ADA) Stabilize Elemental Mercury Wastes. Mixed Waste Focus Area*, Innovative Technology Summary Report, DOE/EM-0472, prepared for Office of Environmental Management, Office of Science and Technology, September 1999. http://apps.em.doe.gov/ost/itsrtmwfa.html.

DOE 1999c. U.S. Department of Energy. *Demonstration of ATG Process for Stabilizing Mercury (<260 ppm) Contaminated Mixed Waste. Mixed Waste Focus Area*, Innovative Technology Summary Report, DOE/EM-0479, prepared for Office of Environmental Management, Office of Science and Technology, September 1999. http://apps.em.doe.gov/ost/itsrtmwfa.html.

DOE 1999d. U.S. Department of Energy. *Demonstration of GTS Duratek Process for Stabilizing Mercury (<260 ppm) Contaminated Mixed Waste. Mixed Waste Focus Area*, Innovative Technology Summary Report, DOE/EM-0487, prepared for Office of Environmental Management, Office of Science and Technology, September 1999. http://apps.em.doe.gov/ost/itsrtmwfa.html.

DOE 1999e. U.S. Department of Energy. *Demonstration of NFS DeHg Process for Stabilizing Mercury (<260 ppm) Contaminated Mixed Waste. Mixed Waste Focus Area*, Innovative Technology Summary Report, DOE/EM-0468, prepared for Office of Environmental Management, Office of Science and Technology, September 1999. http://apps.em.doe.gov/ost/itsrtmwfa.html.

DOE 1999f. U.S. Department of Energy. C.H. Mattus. *Measurements of Mercury Released from Amalgams and Sulfide Compounds*. ORNL/TM-13728.

DOE 2001a. U.S. Department of Energy. *Guidebook to Decision-Making Methods*.

DOE 2001b. U.S. Department of Energy. C.H. Mattus. *Measurements of Mercury Released from Solidified/ Stabilized Waste Forms*. ORNL/TM-2001-17.

DOE 2002. U.S. Department of Energy. *Arrow-Pak Macroencapsulation. Mixed Waste Focus Area.* Innovative Technology Summary Report, OST/TMS ID 2159. Prepared for Office of Environmental Management, Office of Science and Technology.

DPRA Incorporated 1998. *Compliance Cost Estimates for the Proposed Land Management Regulation of Cement Kiln Dust*. St. Paul, MN.

ETC 2001. Environmental Technology Council. *Incinerator and Landfill Cost Data*. May 2001. www.etc.org.

Federal Register 1999. *Potential Revisions to the Land Disposal Restrictions Mercury Treatment Standards (Advanced Notice of Proposed Rulemaking)*. Volume 64, page 28956. May 28, 1999.

Flexicon 2004. Fax to J. Bubb, MPR Associates, September 14, 2004. *FLEXICON Conveyor System for Granulated Metal Powder*.

Fuhrmann, M., D. Melamed, P. Kalb, J. Adams, and L. Milian 2002. *Sulfur Polymer Solidification/ Stabilization of Elemental Mercury Waste*. Waste Management Journal 22 327-333.

GeoEngineers 2004. *Landfill Design and Permitting in Alaska*. Available from: http://www.geoengineers.com/projects_039.asp.

Global Industrial 2004. *Online Catalog*. Available at: www.globalindustrial.com.

Gragg, W, LA Chemical 2004. Email to J. Bubb, MPR Associates, September 7, 2004. *Cascade*.

Grainger 2004. *Online Catalog*. Available at: www.grainger.com.

Harrell, J.L. and J.S. Hotard Jr. 1995. *Macroencapsulation of Hazardous Waste*. U.S. Patent No. 5,471,065.

Industrial Cost Engineering 2003. *Estimates*. Available at http://www.costestimating.com/estimates/index.html.

IT/NFS, 2001. *Expression of Interest for Processing Services of Elemental Mercury using DeHg® for the Defense National Stockpile Center*, Knoxville, TN. September 13, 2001.

Jacobs, N. 2004. Personal communication between Norm Jacobs (NFS) and Geoff Kaiser (SAIC) (and other EPA/ SAIC/ MPR staff), September 7, 2004.

Jones, N.L, 2003. *Notes on Landfill Design.* Department of Civil Engineering, Brigham Young University, CE En 540. Available at: http://class.et.byu.edu/ce540/notes/landfill.pdf.

Kalb, P.D. 2001, Brookhaven National Laboratory. Letter to D. Lynch, Defense Logistics Agency, June 28, 2001. *Sulfur Polymer Stabilization/Solidification (SPSS) Process for Treatment of Elemental*

Mercury, Mercury Contaminated Soils and Debris – Technology Summary: Response to Defense Logistics Agency Request for Expressions of Interest.

Kalb ,P.D., J.W. Adams, and L.W. Milian 2001. *Sulfur Polymer Stabilization/ Solidification (SPSS) of Treatment of Mixed-Waste Mercury Recovered from Environmental Restoration Activities at BNL.* Report for U.S. Department of Energy, BNL-52614.

Lab Depot 2004. *Sodium Sulfide, Fused Flakes (S1470)*. Available at: www.labdepotinc.com.

LACO Technologies 2004. *Liquid Nitrogen Trap Model LNT6200K*. Available at: www.lacotech.com.

Lindgren, Per-Olov, Karin Paulsson, and Anna Svedberg (Bolinden Mineral AB) 1996. *Method for Dealing with Mercury-Containing Waste*. U.S. Patent No. 5,567,223.

Litz, J., T. Broderick, and R. Stewart 2002. *Method and Apparatus for Stabilizing Liquid Elemental Mercury*. United States Patent No. 6,403,044.

Lynch 2002. Letter from D. Lynch, Defense Logistics Agency (Department of Defense), to P. Randall, U.S. Environmental Protection Agency. June 10, 2002.

Morris, M. and G. Hulet 2003. *Development and Selection of Technologies for Mercury Management on U.S. Department of Energy Sites: The MER01-MER04 and Mercury Speciation Demonstrations.* In WM'03 Conference, February 2003, Tucson, AZ.

Morris, M. et al. 2002. *Demonstration of New Technologies Required for Treatment of Mixed Waste Contaminated with ≥ 260 ppm Mercury*. ORNL/TM-2000/147, Oak Ridge National Laboratory, Oak Ridge, TN.

MSC Industrial Supply Company 2004. *Online Catalog*. Available at: www.mscdirect.com.

NEMA 2000. *Environmental Impact Analysis: Spent Mercury-Containing Lamps*. January 2000. www.nema.org

OMB 2004a. Office of Management and Budget. *Discount Rates for Cost-Effectiveness Analysis of Federal Programs*. Federal Register Vol. 69 No. 38 February 26, 2004, pp 8991-8992.

OMB 2004b. *Office of Management and Budget. Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Circular A-94.

Perma-Fix 2001. *Proposal by Perma-Fix for Provision of Elemental Mercury Processing Services*. July 6, 2001. Business sensitive information removed.

Perry, R. and D. Green 1997. *Perry's Chemical Engineers' Handbook. Seventh Edition*. McGraw-Hill, New York, NY.

Randall, P., L. Brown , L. Deschaine , J. Dimarzio , G. Kaiser, and J. Vierow, 2004. *Application of the Analytic Hierarchy Process to Compare Alternatives for the Long-Term Management of Surplus Mercury*. Journal of Environmental Management 71 (May 2004), 35-43.

Randall P. 2005. U.S. Environmental Protection Agency. *Review of Draft Report Titled "Economic and Environmental Analysis of Technologies to Treat Mercury and Dispose in a Waste Containment Facility*. Memorandum to Geoffrey D. Kaiser, SAIC, dated January 31, 2005.

Reddy, D.V. and B. Butul 1999. *A Comprehensive Literature Review of Liner Failures and Longevity*. Florida Center for Solid and Hazardous Waste Management.

RES (Richardson Engineering Services) 2002. *Process Plant Construction Estimating Standards. 2002 Edition*.

Safety-Kleen (Lone and Grassy Mountain), Inc. 2001. Module VI, Hazardous Waste Landfills. *Grassy Mountain Facility, State-Issued Part B Permit*. April 9, 2001. UTD991301748.

Rocky Mountain Arsenal 2004. *On-Post Double-Lined Hazardous Waste Landfills*. Available from: http://www.pmrma.army.mil/.

SAIC 2002. Science Applications International Corporation. *Preliminary Cost Estimate for Long Term Mercury Storage*. Prepared for U.S. EPA Office of Solid Waste through a subcontract with IEC. March 8, 2002.

Salary.com 2004. *Salary Wizard*. Available at: www.salary.com.

Sanchez, F., D.F. Kosson, C.H. Mattus, and M.I. Morris 2001. *Use of a New Leaching Test Framework for Evaluating Alternative Treatment Processes for Mercury Contaminated Mixed Waste (Hazardous and Radioactive)*. Vanderbilt University, Department of Civil and Environmental Engineering. December 14, 2001. Available at http://www.cee.vanderbilt.edu/cee/research_projects.html.

SENES 2001. SENES Consultants Ltd. *The Development of Retirement and Long Term Storage Options of Mercury*. Prepared for National Office of Pollution Prevention, Environment Canada.

Solis, A., Yale North America 2004. E-mail to J. Bubb, MPR Associates, September 9, 2004. *Yale North America - Lift trucks, fork lifts and hand trucks*.

Svensson, Margareta, Bert Allard, and Anders Düker 2004. *On the Choice of Conditions for Geologic Disposal of Hg-Waste: Formation of HgS by Mixing HgO or Elemental Hg with S, FeS, or FeS_2* (extended abstract). Presented at the *7th International Conference on Mercury as a Global Pollutant*, Ljubljana, Slovenia, June 27-July 2, 2004.

Sweden 2003. Swedish Environmental Protection Agency. *A Safe Mercury Repository*. A translation of the official report SOU 2001:58. January 2003.

Ten Siethoff, E., MPR Associates 2004a. Memorandum of August 19, 2004 conference call with EPA, SAIC, and ADA. *ADA/Perma-Fix Sulfide Process*.

Ten Siethoff, E., MPR Associates 2004b. Memorandum of September 7, 2004 conference call with EPA, SAIC, and NFS. *Conversation with NFS on the DeHg Process*.

Ten Siethoff, E., MPR Associates 2004c. Memorandum of September 8, 2004 Telecon with Youngstown Barrel & Drum Company Sales Representative. *Polyethylene-Lined Steel 55-Gallon Drums*.

Ten Siethoff, E., MPR Associates 2004d. Memorandum of September 30, 2004 Telecon with ERS Incorporated. *HDPE Endcaps*.

USACE 1997. U.S. Army Corps of Engineers. *Guidance for Low-Level Radioactive Waste (LLRW) and Mixed Waste (MW) Treatment and Handling*. EM 1110-1-4002.

USDOL 2004. U.S. Department of Labor, Bureau of Labor Statistics. *Bureau of Labor Statistics Data*. Available at: www.bls.gov.

USEPA 1998. U.S. Environmental Protection Agency. *Municipal Solid Waste Landfills. Compilation of Air Pollutant Emission Factors* AP-42, Section 2.4. November 1998.

USEPA 2000. U.S. Environmental Protection Agency. *A Guide to Developing and Documenting Cost Estimates During the Feasibility Study*. EPA 540-R-00-002.

USEPA 2001. U.S. Environmental Protection Agency. *Proceedings and Summary Report*. *Workshop on Mercury in Products, Processes, Waste and the Environment: Eliminating, Reducing and Managing Risks from Non-Combustion Sources*. March 22-23, 2000. Baltimore. EPA/625/R-00/014. June 2001.

USEPA 2002a. U.S. Environmental Protection Agency. *Technical Background Document: Mercury Wastes. Evaluation of Treatment of Mercury Surrogate Waste*. Final Report. February 8, 2002.

USEPA 2002b. U.S. Environmental Protection Agency. *Technical Background Document: Mercury Wastes. Evaluation of Treatment of Bulk Elemental Mercury.* Final Report. February 8, 2002.

USEPA 2002c. U.S. Environmental Protection Agency. *Preliminary Analysis of Alternatives for the Long Term Management of Excess Mercury*. EPA/600/R-03/048, August 2002. A summary of this report has been published in the Journal of Environmental Management (Randall et al. 2004).

USEPA 2002d. U.S. Environmental Protection Agency. *Advances in Encapsulation Technologies for the Management of Mercury-Contaminated Waste*. Prepared by Chattopadhyay, S. and W. Condit, Battelle, Columbus, OH.

USEPA 2003. U.S. Environmental Protection Agency. RCRA, Superfund & EPCRA Call Center Training Module *Introduction to Land Disposal Units (40 CFR Parts 264/265, Subparts K, L, M, N)*. EPA530-R-04-014.

Utah, 2001. *Managing Soil pH in Utah.* Utah State University Extension. AG-SO-07.

Utah 2002. Utah Department of Environmental Quality, Division of Solid and Hazardous Wastes. *Information on Commercial and Federal Facilities*. http://www.deq.state.ut.us/EQSHW/cffs-1.htm

Wagh, A.S.,D. Singh, and S.Y. Jeong 2000. *Mercury Stabilization in Chemically Bonded Phosphate Ceramics*. (author affiliation: Argonne National Laboratory). Presented at the *Workshop on Mercury in Products, Processes, Waste and the Environment: Eliminating, Reducing and Managing Risks from Non-Combustion Sources*. Baltimore, Maryland. Sponsored by U.S. EPA. March 22-23, 2000.

Wong, K.V, G. He, and H. Solo-Gabriele 1997. *Infiltration Rates through Synthetic Caps and Side Slopes at Landfills*. January 1997. University of Miami (Florida). Report No. 97-12.

Zhang, Jian and P.I. Bishop 2003. *Stabilization/ Solidification of High Mercury Wastes with Reactivated Carbon*. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. pp 31-36.

5.2 References Used for Comparative Analyses of Options A-F

Bjästa Återvinning 2001
BNL 2001
Bowerman et al. 2003
Bubb 2004b
Butz 2004
Davis and Osucha 1998
DOE 1994, 1999a, 1999f
Fuhrmann et al. 2002
IT/NFS 2001
Jacobs 2004
Kalb 2001
Kalb et al. 2001
Lindgren et al. 1996
Morris and Hulet 2003
Perma-Fix 2001
Sanchez et al. 2001
Svensson 2004
SENES 2001
Ten Siethoff 2004a, 2004b
USEPA 2002a, 2002b, 2002c, 2002d
Zhang and Bishop 2003